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DEVELOPMENT OF AN ECONOMIC ANALYTICAL FRAMEWORK FOR SOLID WASTE POLICY ANALYSIS

Jeffrey Hall, et al

Environmental Dynamics, Incorporated

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by

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This report presents the development of a micro-economics/systems overview of the problems of solid waste generation and control. A benefit measure is developed and recommended for use in evaluating solid waste management policy decisions. The benefit measure incorporates the consumers' surplus approximation to welfare loss, changes in firms' profits and government revenues, and costs of solid waste disposal. The benefit measure is used to develop a series of taxation (taxes may be negative) models for the purpose of control of the solid waste stream. The models produce taxes which lead to the benefit maximizing solid waste levels. The models include substitutional possibilities in production and consumption and use market observable functions as their base. A property rights system is examined and it is concluded that such a system has no advantages over the taxation of solid wastes. Economic incentives for encouraging forth supplies of recyclable materials are examined. It is concluded that the collateral policies of solid waste taxation and the subsidization of suppliers of recyclable materials provide highly workable management tools for the purposes of solid waste control and recycling encouragement.

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FOREWORD

Man and his environment must be protected from the adverse effects of pesticides, radiation, noise, and other forms of pollution, and the unwise management of solid waste. Efforts to protect the environment require a focus that recognizes the interplay between the components of our physical environment--air, water, and land. The Municipal Environmental Research Laboratory contributes to this multidisciplinary focus through programs engaged in

- studies on the effects of environmental contaminants on the biosphere, and
- a search for ways to prevent contamination and to recycle valuable resources.

As part of these activities, this report describes a study of benefit and cost criteria that should be utilized in the assessment of policies designed to control solid waste flows.

A. W. Breidenbach, Ph.D.
Director
Municipal Environmental
Research Laboratory

ABSTRACT

This report presents the development of a micro-economics/systems overview of the problems of solid waste generation and control. A benefit measure is developed and recommended for use in evaluating solid waste management policy decisions. The benefit measure incorporates the consumers' surplus approximation to welfare loss, changes in firms' profits and government revenues, and costs of solid waste disposal.

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SECTION I

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The results of this study indicate that, even in a world of substitution taxation procedures for the control of solid waste can be developed. Such procedures are based upon consumers' surplus, profit loss, and changes in tax revenues. The models are fairly "information intensive" because of substitution possibilities; as a result, when information costs are too high, the report recommends the taxation of solid wastes directly rather than the taxation of goods producing solid wastes. Because of information requirements, the report concludes that the taxation of solid wastes in conjunction with various recycling incentives provides a better policy than one based upon "property rights." The report contains the optimal taxes as functions of the parameters of the problem, for both competitively and monopolistically produced goods.

Which set of policy approaches is to be preferred will generally depend upon the specifics of the problem under consideration.

RECOMMENDATIONS

The results of this report suggest a wide variety of opportunities for empirical research. First of all, as the report shows, it is quite important to derive Solid Waste Authority (SWA) disposal cost functions (see Section IV). An important concomitant is to derive or estimate waste disposal response functions due to specific policies (e.g., solid waste taxation or recycling incentives). As the taxation section indicates it is very important to estimate demand and production cost functions for goods leading to significant amounts of solid wastes. Such components are crucial ingredients of any procedure designed at deriving a good set of policies. In addition, it is desirable to obtain estimates of littering response due to

specific policies.

The report also suggests that it is highly desirable to attempt to find out whether or not the Darnay and Franklin claim of a relatively fixed demand for recycled materials is actually true (see page 123). If their hypothesis is true, then the implications for providing recycling incentives are quite severe. On the other hand if their claim is only true because of relatively inflexible capacity constraints at the recycling processing stage, then a different set of policy alternatives suggests itself (i.e. relieve these constraints).

Finally, a thorogh study is needed to determine the technical and institutional problems associated with a SWA entering the salvage or recycling industry.

SECTION II

INTRODUCTION AND SECTION SUMMARIES

INTRODUCTION

Society, during the last several years, has become more aware and concerned with the effect of its consumption and production decisions upon the environment. This concern is evidenced by the status of air and water pollution as major public issues. A more recent addition is the growing concern with the implications of increasing rates of generation of solid wastes. This concern has become even more acute as rising disposal costs, a dwindling number of available land-fill sites, and increased concern with air and water quality have caused the problem of solid waste disposal to become a major issue in many American cities.

This report deals with the problem of solid waste generation from a micro-economics-systems point-of-view. In particular, the points of the economic system at (i) which significant solid waste decisions are explicitly or implicitly made and at (ii) which various policy tools to control the rate of generation of solid wastes can be implemented are both fully discussed throughout the report.

The study deals with the problems of solid waste generation and the latter's control in a world of substitution. In addition, the study seeks to include and account for the complexities posed by the existence of monopolistic elements and other problems of "second best."

Notions of economic efficiency in solid waste management are fully dealt with and discussed in terms of required data to make such notions operational. The measures of economic efficiency are in terms of market observables as opposed to the "utility"measures commonly used.

While not explicitly included in the models presented, the practical

problems of implementation, monitoring and enforcement costs, and financial constraints of municipal authorities are discussed. In addition, this latter type of discussion is often used to recommend one policy over another.

SECTION SUMMARIES

Section III develops some simple micro economic models which indicate the basic parameters which affect the decisions of micro units (firms and households) as far as solid waste decisions are concerned. The models are used to underscore that substitution is generally the rule and therefore substitution possibilities must be taken account of when reaching policy decisions which are meant to affect the generation of solid wastes. In particular, factor mixes and factor prices, salvage prices, waste disposal costs, littering fees, etc. are all discussed as important parameters to which micro units will respond.

Section IV deals with the methodology with which to compute the waste disposal cost function of a solid waste authority (SWA) as a function of the solid waste loading. The purpose of developing the procedure by which such a function can be computed is that the savings in waste disposal costs must be estimable in order to partially evaluate the effect of a given policy. The models developed take account of alternative technological possibilities for solid waste disposal, land constraints, environmental quality standards, and economies-of-scale. The required data input to make the computation of the SWA's cost function feasible is described and examples are referenced where such studies have actually been carried out.

Section V develops the benefit measure recommended to evaluate solid waste policy decisions. The measure has three major components. The first is the "consumers' surplus" approximation to the "equivalent variation." The main advantage of this component is that it provides a quantifiable measure of the effect upon consumers of policies which

lead to price changes of various consumer goods. The consumer's surplus approximation to the equivalent variation is, of course, composed of integrals of market demand functions of affected consumer goods.

A second component of the benefit measure is the effect upon production costs and tax revenues due to a solid waste policy. The changes in production costs must be considered since they affect firms' profits and hence, through dividends, individual's incomes. Similarly, the change in tax revenue must be considered since such changes represent changes in the level of government services.

The third major component of the benefit measure is the SWA's waste disposal costs.

Section VI deals with the general topic of solid waste taxation models. The taxation models are intended to be applicable institutionally to a mixed economy, such as that of the U.S., in which profit maximizing firms and utility maximizing individuals control most or all of production and the supply of productive inputs, while solid waste collection, processing and disposal are controlled directly by a SWA. In the models production and factor services that give rise to solid waste are only indirectly controlled by the SWA through taxes (possibly negative) that it can levy on certain commodities. For the first set of models the SWA is assumed to optimize net benefits related to the consumption of final output subject to certain constraints required by the economic relations of the private sector of the economy. Thus, these taxes are intended to decentralize the functioning of the economy in the sense that when taxes of the magnitude determined by the model are actually imposed, private firms are induced to achieve precisely those levels of production that in fact yield the optimum level of benefits.

Another way of describing the analytic framework is that we are

considering situations of the "second best" where we are willing to tolerate, say, monopolistic behavior on the part of certain firms but that we may, in part, attempt to correct such behavior. In the models developed, the prices of consumer goods are the decision variables. However, the resulting optimal prices are not to be legislated directly but rather they are used to compute the optimal taxes which, if imposed, will lead the private sector to an equilibrium at whose prices net benefits are optimized.

The models are formulated in terms of observable market relations as opposed to the usual taxing models which are couched in terms of individual utility functions and/or social welfare functions which are all but, perhaps, impossible to measure. These observable functions include market demand and supply curves, monopolistic firms' production cost functions, and solid waste "production functions," all of which are amenable to econometric measurement or approximation. The models also allow the authority choice of the various levels in the production processes at which to intervene. The main reason for considering many decision points (sectors or levels) of production and consumption at which to intervene with taxes is that even though the apparent level at which to tax is at the solid waste disposing level, policy instruments at other levels provide us with a more flexible model and hence if such taxes can be computed, the net benefits to society will be greater than if taxes are only imposed upon solid waste itself.

However, this section fully discusses the informational requirements of the models, and it is concluded that the taxation of only solid wastes has many advantages from an operational point-of-view.

The models fully take account of the fact that there is generally a great deal of substitutional possibilities available to producers and consumers that would affect the generation of solid wastes. Such models, we believe, significantly add to the model of Kneese, Ayres, and d'Arge[1] which assumes a world of nonsubstitution.

The framework for formulating a solid waste taxation approach has been discussed by Guéron[2] in a fairly general and formal framework. Her approach is to maximize a general social welfare function which is discussed only schematically in terms of its arguments. Guéron does not discuss how to compute taxes nor does she explore the issue of decentralization.

Section VII deals with an explicit policy tool available to a SWA. In particular, the issue of a fixed number of "property rights" which guarantee the holder of such rights the ability to dispose of an equivalent number of unit of solid wastes. Presumably a market for the sale and purchase of such rights would arise and an equilibrium price arrived at. Such a scheme is recommended by Dales[3] in the context of water pollution. This section develops the objective function which such a procedure maximizes and criticizes the recommendation based upon the nature of the resulting objective function. The section also fully discusses the practical problem associated with such a system and concludes that in order to be operational, the informational requirements are probably at least as great as those which such a system was originally intended to overcome.

The last section, Section VIII, deals with incentives for recycling. Darnay and Franklin[4] conclude that secondary materials have difficulty competing with virgin materials primarily because the price of those materials reflects only costs of production and does not include the social costs the virgin material's use entails. In this section we have sought to develop policy approaches that will make the relative prices of virgin and secondary materials reflect the disposal cost savings associated with recycled resources. Such a policy will tend to encourage increased efforts at recycling and reduce the demand for disposal services.

There are two basic types of approaches that are of interest in encouraging the increased use of secondary materials: taxes on virgin

materials and subsidies to recycled materials. Both results in an upward shift of the demand price curve for secondary materials. It is shown that for any virgin materials tax that there is a subsidy that will have an identical effect on the secondary materials market. However, because a virgin materials tax, unlike a subsidy, tends to have undesirable secondary effects in production and consumption decisions, it is concluded that subsidies represent a preferable approach.

Subsidies can, of course, be imposed at a number of different points in the system. It is shown though that if municipalities face differing marginal disposal costs (as one would anticipate they do), the optimal subsidy will tend to differ from municipality to municipality. It is thus concluded that societal benefits will be maximized if subsidies are imposed by the local solid waste authority (SWA) and offered to the individuals, firms, and organizations involved in collection of secondary resources in the community. It is furthermore shown that under certain simplifying assumptions the optimal subsidy is equal to the ex post marginal disposal costs.

These subsidies, however, involve difficult monitoring problems. In particular, it may be difficult to verify that the secondary materials collected originated in the municipality seeking to encourage recycling. Thus, there is the danger that one area will end up subsidizing the recycling of residuals generated in another area. Another practical problem with this approach is that it will probably impose a severe financial burden on the local SWA (i.e., the subsidy payments will probably greatly exceed the reduction in disposal costs).

Because of these problems, we consider the possibility of entry by the local SWA into the salvage industry. It is visualized that the SWA would engage in the collection and resale of secondary resources in addition to its traditional waste disposal activities. Because of its size, the SWA would be able to benefit from any economies-of-scale. Furthermore, to the extent that collection of recyclable

items could be combined with regular waste collection, the SWA would have an additional advantage. Because of the possibility that transaction and information costs may preclude direct subsidies to individuals and firms generating recyclable wastes, the analysis assumes that cooperation is encouraged through advertising expenditures. In this case, it is shown that the optimal procedure is to equate the marginal costs of recycling, including marginal advertising expenditures, and the demand price for recycled materials plus marginal disposal costs.

Finally, we turn to the possibility of combining the SWA salvage operation with a waste disposal tax. As collateral policies one would expect that the effectiveness of each would be increased; indeed, it is possible that analyzed separately each will be found ineffective, but when imposed jointly, the results will be a significant increment in benefits to society. The reasoning is that the presence of a waste disposal tax will act as an additional incentive to recycling, while the pressure of a recycling alternative to disposal will result in greater responsiveness of waste generating units to the tax. The optimal tax and advertising expenditure is derived but is shown to involve great informational requirements. A more practical (although sub optimal) approach is then discussed in which marginal cost disposal taxes are imposed and then advertising expenditures are set optimally given the tax level.

SECTION III

PARAMETERS WHICH AFFECT

SOLID WASTE DECISIONS OF MICRO UNITS

The purpose of this section is to present some simplified models which indicate the basic parameters and substitution possibilities to which micro units (e.g., firms and households) respond when making decisions which affect types and quantities of solid wastes. Such models indicate the likely policy tools available for regional solid waste management decisions. In addition, this section serves the purpose of stating the make-up of the aggregated functions which are used in the models developed in later sections.

FIRMS

Let q denote the output level of a firm which uses factors of production indexed by $k = 1,..F$, and let $x_1,..,x_F$ denote the factor input levels. Let p_k, $k = 1,..,F$, denote the per unit price of factor k and let $\phi(x)$ denote the firm's production function, where $x = (x_1,..,x_F)$. Also, assume there are I types of wastes, indexed by $j = 1,..,I$, which are functions of the levels of factor inputs and which are denoted as $w(x) = (w_1(x),..,w_I(x))$. We are assuming that the vector w(x) denotes those wastes which the firm wants to dispose of. Without loss of generality, we can ignore those wastes of the firm's production process which are reused by the firm itself. Let s_j, $j = 1,..,I$, denote the "salvage value" of each unit of waste type j where, of course, s_j may be negative, zero, or positive. Some explanation of s_j is in order. If a firm is charged τ_j, say, for each unit of waste type j and the firm can also receive γ_j for each unit of waste type j provided to another firm, then $s_j = -\tau_j$ if waste is "disposed" of, and $s_j = \gamma_j$ if waste is sold for, say recycling. Let $D^{-1}(q)$ denote the inverse demand function for the firm's product and let MR(q) denote the marginal revenue function.

Then, the firm's optimization problem is

$$\begin{aligned} \max_{q,x} \; & D^{-1}(q)\, q - \sum_{k=1}^{F} p_k x_k + \sum_{j=1}^{I} s_j w_j(x) \\ \text{s.t.} \quad & \phi(x) - q \geq 0 \\ & q \geq 0, \; x \geq 0. \end{aligned} \tag{1}$$

The objective is, of course, just the firm's profits. The first order conditions for an interior optimum are that x^* satisfies

$$\left[q \frac{dD^{-1}(q)}{dq} + D^{-1}(q) \right] \frac{\partial \phi(x)}{\partial x_i} - p_i + \sum_{j=1}^{I} s_j \frac{\partial w_j(x)}{\partial x_i} = 0, \tag{2}$$

for $i = 1,..,F$.

Noting that $q \frac{dD^{-1}(q)}{dq} + D^{-1}(q)$ is just the marginal revenue function, it is clear that the first order condition says that at the optimum the increment to total revenue from the use of an additional unit of the $i^{\underline{th}}$ factor equals the price of that factor plus the increased disposal cost. It is of course impossible to express x^* in closed form. The conditions (2) do however show that the optimum factor usage, x^*, depends upon the vectors p and s and hence the waste vector $w(x^*)$ also depends upon p and s. Therefore, we see that the firm's output levels of wastes, $w(x^*)$, can be affected by somehow altering the factor price vector p and/or the waste salvage vector s. For instance, a firm may be encouraged to use more of a factor which represents recyclable material than some other factor which represents virgin material by altering the relative corresponging factor prices (e.g., altering the factor price vector p). Similarly, a firm may be encouraged to present some type of waste to, say, another firm if the salvage price vector s can be altered, or may be encouraged to produce less of some waste type by decreasing the salvage value of that particular waste type through say, a taxing mechanism. In fact, we can also conceive of a per unit tax τ upon the firm's level of production. In this case the objective in (1) has the additional term $-\tau q$, and the corresponding first

order conditions are

$$\left[q \frac{dD^{-1}(q)}{dq} + D^{-1}(q) - \tau\right] \frac{\partial \phi(x)}{\partial x_i} - p_i + \sum_{j=1}^{I} s_j \frac{\partial w_j(x)}{\partial x_i} = 0 \quad (3)$$

for $i = 1, 2, .., F$.

Therefore, besides outright legislation, a firm's output levels of its own product and resulting waste production can be altered by some combination of changing the firm's per unit revenue price, changing the firm's per unit input price vector, and/or changing the firm's per unit waste salvage price vector. In later sections we will discuss general taxation (including negative taxes) models for finding appropriate taxes upon firms' outputs, inputs, and wastes.

It is important to observe that this general formulation implies a great deal of substitution possibilities for the firm. For instance, a tax upon the firm's product will not only affect the level of the firm's output, but will also affect the **manner** by which the firm produces the resulting new level of output and thereby will affect the levels of the various wastes produced by the firm. The imposition of, say, factor taxes and/or waste taxes (possibly negative) will also affect the level of the firm's output as well as the manner by which it produces that output and hence will also affect the nature of the firm's mix of wastes and the waste content of its output. In particular, a mechanism by which the salvage price of waste type 1 is changed from, say, \$-1 to \$1 (perhaps through the organization of a currently nonexistent solid market) would greatly affect the revenue position of the firm and encourage it to provide its quantity of waste type 1 to those who desire it at this price (see Section VIII for more discussion of this matter). Naturally, this may encourage the firm in question to produce more waste type 1 than before; however, as we shall see in later sections, this in no way is socially damaging if positive prices for waste materials are set appropriately.

While the above discussion is focused upon those wastes which are the immediate result of the firm's production process, there is another type of waste which is also important to consider. In particular, physical commodities (as opposed to purely service goods) embody a "solid waste potential." That is, items such as newspapers or other items which are packaged imply a certain amount of solid waste disposal demand on the part of final consumers of the firm's product. The above model which includes a tax upon the output of the firm does not capture the essence of the problem. That is, it seems reasonable in the context of solid waste problems that taxes upon consumer goods should be based upon the "solid waste potential" of those goods.

Assume that for a particular firm producing a final consumption good we can identify a function $w_o(x)$ which represents the solid waste potential of the firm's product when the factor $x = (x_1,..,x_F)$ is used. We assume, for simplicity, that w_o is a scalar, say weight or volume of solid waste potential. If a tax of s_o' is imposed upon each unit of solid waste potential, the fim's first order conditions for an interior optimum x^* are

$$\left[q\frac{dD^{-1}(q)}{dq} + D^{-1}(q)\right]\frac{\partial\phi(x)}{\partial x_i} - p_i + \sum_{j=o}^{I} s_j \frac{\partial w_j(x)}{\partial x_i} = 0 \qquad (4)$$

for $i = 1, 2,..,F$, and where $s_o = -s_o'$. Essentially, we see that this new model just adds a new waste type that the firm must consider. This new waste type, the "solid waste potential," can be thought of as the solid waste burden imposed upon the consumers of the firm's product. The justification of a solid waste potential tax upon consumer goods, rather than an ordinary excise tax, is that the tax itself makes explicit to producers that less solid waste potential is desired. Also, contrary to, say, a solid waste collection tax upon consumers, such a solid waste potential tax

upon producers does not encourage consumers to substitute into socially undesirable disposal techniques such as littering or incineration.

For simplicity, we assume the immediate wastes the firm offers for disposal correspond to those with nonpositive salvage values. That is, let

$$I_d = \{j | s_j \leq 0,\ j = 1,..,I\} \tag{5}$$

(i.e., I_d is the set of indices over waste types such that the salvage value is negative). Then, the total weight or volume a firm offers for solid waste disposal services is given by

$$w(x^*) = \sum_{j \in I_d} w_j(x^*) \tag{6}$$

Recall, x^* is a function of p and s and hence depends upon those policies which are meant to affect these prices. The addition of all vectors $w(x^*)$ over all the firms of the region in question yields the aggregate demand function of firms for solid waste disposal services as a function of the vector arguments p and s.

Hence, because of the generally great substitution possibilities available to firms (especially in the long-run), solid waste policies will have various effects upon the levels of production of various solid waste types and hence upon the societal costs of disposing of these wastes. Needless to say, influencing the price vectors p and s requires a generally great understanding of the aggregate market conditions which ultimately determine prices and quantities for the factors and waste types under consideration.

The section dealing with taxation models discusses more fully the problematic aspects which are raised above.

HOUSEHOLDS

Similar models can be developed for a household's waste generation decisions. Assume the household utility function U depends upon the goods it consumes and assume the household budget is B. Let

$w_{io}(q_i)$, $i = 1,..,n$, denote the "solid waste potential" inherent in q_i units of the $i^{\underline{th}}$ consumer good and assume there is a per unit charge of τ upon the household's solid waste. That is, for simplicity, we are assuming the units of measurement of $w_{io}(q_i)$, $i = 1,..,n$, are the same (e.g., weight or volume). Let r_i, $i = 1,..,n$, denote the per unit price of the $i^{\underline{th}}$ consumer good. The household then seeks to

$$\underset{q \geq 0}{\text{maximize}}\ U(q_1,q_2,..,q_n) \tag{7}$$

$$\text{subject to} \sum_{i=1}^{n} [r_i q_i + \tau w_{io}(q_i)] \leq B \quad .$$

We therefore see that if q^* is an optimal consumption vector for the household, the household's total demand for solid waste disposal

$$w_o(q^*) = \sum_{i=1}^{n} w_{io}(q_i^*) \quad , \tag{8}$$

(measured by, say, volume or weight) depends upon the consumer goods price vector r as well as upon the solid waste disposal tax τ. Also, since the vector r and $w_{io}(q_i)$, $i = 1,..,n$, depend upon the vectors p and s of the firm waste disposal model, we see that household solid waste depends, to a great extent, upon policies in the production sector. Aggregating over all households of the region in question, we then obtain the regional household demand for solid waste disposal services. Note that the household model can easily be extended to include waste types rather than just a single measure of waste (weight or volume).

We wish to point out that neither of the above formal models explicitly includes the possibility of substitution of some other method for solid waste disposal in place of the usual collection services. For instance, a household (or firm) may be encouraged to litter when a solid waste tax τ is imposed. If the cost of littering including psychological costs, is less than τ, the above simple model would imply that the household would litter (or, perhaps, incinerate) its solid waste. However, to the extent that such behavior as littering or incinerating all solid waste is unlikely,

the model can be somewhat sharpened by including littering explicitly into the utility function of the household. That is, certeris paribus, the more the household litters, the smaller its utility. With this minor addition to a formal model, we then see that households would generally trade-off the disutility associated with an increment of littering with the additional effective increment to its budget that would result.

In fact, let U depend upon consumption goods as well as ℓ and d, the quantities respectively of wastes littered and legally disposed of. Let τ_ℓ be the per unit charge of littering and let τ_d be the solid waste disposal charge. We assume $\partial U/\partial \ell \leq 0$ and $\partial U/\partial d \geq 0$. The household can then be assumed to solve

$$\begin{aligned} &\text{maximize } U(q_1,..,q_n,\ \ell,\ d) \\ &\text{subject to } \sum_{i=1}^{n} r_i q_i + \tau_\ell \ell + \tau_d d \leq B \\ &\ell + d - \sum_{i=1}^{n} w_{io}(q_i) = 0 \\ &q,\ \ell,\ d \geq 0 \ . \end{aligned} \tag{9}$$

The Lagrangian for this problem is

$$\begin{aligned} L = U(q_1,..,q_n,\ell,d) &- \lambda\Big(\sum_{i=1}^{n} r_i q_i + \tau_\ell \ell + \tau_d d - B\Big) \\ &-\gamma\Big(\ell+d - \sum_{i=1}^{n} w_{io}(q_i)\Big) - \rho q - \nu \ell - \mu d, \end{aligned} \tag{10}$$

where we have also assigned multipliers to the nonnegativity constraints. Observe that if $\tau_\ell \geq \tau_d$, then the household will not litter. Therefore, assume $\tau_\ell < \tau_d$ and let q*, d*, ℓ* be optimal for household. Let $\lambda^*,\gamma^*,\rho^*,\nu^*,\mu^*$ be the values of the multipliers which correspond to q*, d*, ℓ*. That is,((q*, d*, ℓ*), (λ^*,γ^*, ρ^*, ν^*, μ^*)) is a Kuhn-Tucker point of the Lagrangian. Then the household's first order conditions for an interior optimum q*, d*, ℓ* imply

$$\frac{\partial U(q^*, \ell^*, d^*)}{\partial \ell} - \lambda^* \tau_\ell - \gamma^* = 0 \qquad (11)$$

and

$$\frac{\partial U(q^*, \ell^*, d^*)}{\partial d} - \lambda^* \tau_d - \gamma^* = 0 \qquad (12)$$

or, equivalently,

$$\lambda^*(\tau_d - \tau_\ell) = \frac{\partial U(q^*, \ell^*, d^*)}{\partial d} - \frac{\partial U(q^*, \ell^*, d^*)}{\partial \ell} \qquad (13)$$

That is, at the household optimum, the marginal utility of disposing of wastes properly minus the marginal utility of littering must be proportional to the difference between the disposal and littering taxes and where the proportionality factor, λ^*, is the marginal utility of income evaluated at the optimal bundle q^*, ℓ^*, d^*.

The above model implies that if induced littering is to be avoided, then merely set $\tau_\ell > \tau_d$. However, the cost τ_ℓ is a perceived cost and, as such, a great deal of societal resources may have to be expended before individual households perceive a relatively large littering fee. In fact, advertising campaigns for reduced littering can be viewed as an attempt to decrease the individual's marginal utility of littering, while threatened fines for littering are an attempt to affect the perceived littering charge.

The section dealing with solid waste taxes will have more to say about how to minimize induced littering. In particular, while solid waste collection taxes are attractive one must recognize that there will be some amount of induced littering that will offset some of the societal benefits of the tax. As such, a practical policy may be to discourage induced littering by offering the household (and firms for that matter) free collection of certain waste constituents (e.g., newspapers or aluminum cans). Such a policy would have the double effect of (i) reducing the household's total waste disposal fee, and (ii) providing a relatively large supply of a recyclable material which may, in turn, encourage

capital expansion in processing facilities (e.g., deinking plants).

In summary, the above simplified models indicate the interdependencies that exist and that generally cannot be ignored when attempting to arrive at policy decisions regarding solid wastes. For example, recycling may be encouraged by intervening in factors of production markets. However, altering factor prices affects the quantities of goods produced and their waste potential, as well as the quantities of the factors (and other factors) in question. As a result, while recycling a particular commodity has increased, there may also be significant detrimental effects elsewhere in the system which could generally include the greater production of some other waste types. In particular, general equilibrium problems abound in this area and they must be dealt with or at least understood before specific policy decisions are made.

In Section V we explicitly discuss the generation of a measure of the welfare effects of various policy approaches. This measure is based upon the response of supply and demand for consumer goods. Thus, the measure and consequently the appropriateness of any policy is explicitly dependent on the substitution possibilities and interaction of economic agents discussed above.

SECTION IV

WASTE DISPOSAL COST MODELS

As has been previously pointed out, any policy analysis must be able to estimate the solid waste disposal (regional) cost as a function of solid waste loading. If this can be accomplished, then savings in solid waste disposal costs can be estimated if waste loadings are reduced (presumably through a taxing and/or recycling subsidy mechanism).

Naturally, the regional cost of solid waste disposal depends crucially upon the nature or mode of disposal. That is, there is a significant number of ways by which regional solid waste can be disposed of and therefore the cost of disposal depends upon the mix of technologies used.

Therefore, it is the point-of-view of this report that in order to develop a notion of economic efficiency for solid waste policy analysis, the most appropriate regional disposal cost measure that can be used is the one which achieves the minimum cost of disposing of a given waste loading. Therefore, the appropriate cost function to be used is an "optimal value function" in the sense that the cost function is a result of an optimization problem which has the waste loadings as exogenous inputs. Hence, for a given waste loading an optimization problem is solved and the resulting cost (as a function of the given waste loading) is, by definition, the minimum cost of disposal of the waste loading.

The remainder of this section is devoted to the development and discussion of the disposal cost models. In general, the construction of such models for actual implementation is in itself a considerable task. Therefore, the models presented below will clarify to a great extent the type of data inputs required to make such models operational. As we shall see, although the data input requirement is considerable, it is by no means an insurmountable task to gather such data.

We first develop a static or steady-state solid waste disposal cost model, and later on discuss the dynamic or time-varying analogue.

Steady-state or static models, which usually severely abstract from reality, have the advantage that their more tractable construction leads to a relatively clear statement of required data inputs. It is in this latter spirit that we first develop such a model.

The word "region" is meant to connote an amorphous geographical enclosure which "bounds" the area under consideration. As such, the "region" is itself an exogenous input which may generally easily be decided upon in actual applications.

A region, among other things, gives rise to solid waste types. For instance, the most common can be taken to be general refuse, construction and demolition wastes, garden prunings, manures, garbage, and industrial rubbish. Of course, manures are typical of regions with a fair amount of agricultural activity. Also, the above categories can be further expanded upon (or shortened as the need may be).

We can think of the above waste types as emanating from waste origins. For instance, the usual types of origins are residential or domestic, municipal (includes commercial and construction and demolition wastes), industrial, and agricultural.

In order to develop a better feel for the composition of wastes from various waste origins we present the following data which, along with part of the discussion above, are taken from Pathak [5] .

Typical residential or domestic solid waste is composed of as follows: paper - 50%, garbage - 12%, garden waste - 9%, metals - 8%, ceramic and glass - 7%, wood - 2%, cloth - 2%, rubber - 1%, leather - 1%, plastics - 1%, unclassified - 7%.

Typical municipal waste is composed as follows: paper - 54%, garbage - 15%, grass and leaves - 10%, tin cans and other metals - 7%, ashes and dirt - 5%, glass - 3%, wood - 2%, rags - 2%, leather and

rubber - 1%, synthetics - 1%. Therefore, generally, municipal and domestic solid wastes have more or less the same composition.

Industrial solid wastes are slightly more difficult to describe generally and usually may vary significantly with the region in question (e.g., there may be a mining industry in the region). However, besides those solid wastes that are peculiar to the industry in question, there are industrial solid wastes which perhaps are typical and these include paper, wood, rags, and metals. Pathak found for the region under his consideration the composition by volume of industrial rubbish is: paper - 61.1%, wood - 18.5%, rags, -2.2%, plastics - 0.9%, garbage - 1.1%, ferrous metals - 2.9%, glass - 1.5%, miscellaneous - 5.8%, ashes and soil - 6%. Therefore, besides wood, the composition of non industry-specific solid waste is more or less the same as that for domestic and municipal wastes.

Those wastes which are industry specific would have to also be taken account of in an actual application by collection of the appropriate data.

Besides waste types generated in a particular region, there is also a number of waste disposal technologies available, and costs vary with the chosen mix of technologies.

The most widely used technology is, of course, sanitary landfill. Therefore, the land available to the region in question may be or may become a severe limitation for the usage of this method in that region. It should be pointed out that disposal costs generally depend upon location. For example, one must consider transportation costs to remote sanitary landfill sites relative to less remote sites.

Incineration is another common method which has the main attractiveness of easing the pressure upon land for the purposes of sanitary landfill. Of course, besides incineration costs, additional costs incurred because of air pollution requirements or constraints must also be taken cognizance of. In a region where air pollution requirements are stringent, electrostatic precipitators, for instance, may be required to clean up emissions.

A newer type of incineration process, pyrolysis, which is a high temperature incineration process carried out in the absence of air, may prove beneficial from an air pollution point of view. Complex gases break down in the 900-1200^{o}C range to yield simple gas products with a relatively high fuel value [5]. Also, the residual ash can be processed for organic chemical recovery or land filled.

There are also several other processes such as anaerobic digestion, wet oxidation, and composting.

Besides the usual form of incineration, there is also the possibility of, say, utilizing refuse for the purpose of electric power generation . It is expected that plants which utilize pulverized coal as a main fuel source can also utilize milled refuse.

The purpose of the above discussion is to point out that there are generally many alternatives for the treatment and ultimate disposal of solid wastes. The alternatives may generally be region specific as well as such constraints as air and water pollution limitations. For this reason, each region may have its own best way to treat and dispose of the regions's solid wastes.

STEADY-STATE COST MODEL I: NO TREATMENT CAPACITY ADJUSTMENT

This simple model is presented both as a means of introducing notation as well as for its appropriateness for short-run situations.

We assume there are I types of wastes indexed by $i = 1,..,I$; J locations at which these wastes are "generated," indexed by $j = 1,..,J$; and L locations to which wastes can be sent, indexed by $\ell = 1,..,L$. Let w_{ij} denote the amount of waste type i generated at location j. At this point some notion of the word "generated" is needed. A waste generation point is to be thought of as an area lumped into one point or as an intermediate point from which wastes can further be transported to other treatment or disposal facilities.

Let $c_{i\ell}$ be the cost function for treating waste type i at location ℓ. Also, let $\alpha_{ij\ell}$ be the proportion of waste type i generated at point j

which is to be sent to location ℓ for treatment and disposal. (In this model we assume disposal takes place at the location of treatment. Therefore, we are temporarily ruling out incineration at one location and land fill of the residue at another location.)

Also, we assume the technology type at location ℓ is known and that we are not going to "expand" the waste disposal treatment system. We also assume that at each location ℓ there is an upper bound $u_{i\ell} \geq 0$ on the quantity of waste type i that can be treated at location ℓ.

With the above notation, the quantity of solid waste of type i which is sent to location ℓ is

$$\sum_{j=1}^{J} \alpha_{ij\ell} w_{ij} \tag{14}$$

and therefore the cost of treating waste type i at location ℓ is

$$c_{i\ell}\left(\sum_{j=1}^{J} \alpha_{ij\ell} w_{ij}\right) \tag{15}$$

and then the total treatment cost over the entire regional system is given by

$$\sum_{\ell=1}^{L} \sum_{i=1}^{I} c_{i\ell}\left(\sum_{j=1}^{J} \alpha_{ij\ell} w_{ij}\right) \quad . \tag{16}$$

Also, there are pollution constraints which must be met at each one of the waste disposal locations $\ell = 1,..,L$. Formally, let $P_{i\ell}$ be the pollution function for treating waste type i at waste treatment and disposal location ℓ. Then, the amount of pollution to occur at that location is given by

$$P_{i\ell}\left(\sum_{j=1}^{J} \alpha_{ij\ell} w_{ij}\right) \quad . \tag{17}$$

This implies that the best selection of treatment alternatives can be found by solving the optimization problem

$$c(w) = \underset{\alpha}{\text{minimize}} \quad \sum_{\ell=1}^{L} \sum_{i=1}^{I} c_{i\ell} \left(\sum_{j=1}^{J} \alpha_{ij\ell} w_{ij} \right)$$

$$\text{subject to} \quad \sum_{\ell=1}^{L} \alpha_{ij\ell} = 1, \quad i=1,..,I, \; j = 1,..,J \tag{18}$$

$$\sum_{j=1}^{J} \alpha_{ij\ell} w_{ij} \leq u_{i\ell}, \; i = 1,..,I, \; \ell = 1,..,L$$

$$P_{i\ell} \left(\sum_{j=1}^{J} \alpha_{ij\ell} w_{ij} \right) \leq \bar{P}_{i\ell}, \; i = 1,..,I, \; \ell = 1,..,L$$

$$\alpha_{ij\ell} \geq 0, \text{ all } i, j, \ell,$$

and where $\bar{P}_{i\ell}$ are the maximum allowable pollution levels corresponding to treatment of waste type i at location ℓ.

Therefore, the regional waste disposal cost function, for a given waste loading $w = (w_{11},..,w_{ij},..,w_{IJ})$, denoted by $c(w)$ is computed by solving the above optimization problem. Therefore, in principle, if the above optimization problem can be solved, the cost function $c(w)$ is at hand in tabular form.

At this point some remarks are in order regarding the nature of $c(w)$ as well as the ease of constructing such a regional treatment model. Even though this first model is a somewhat oversimplification, the remarks to be made apply equally to the more complete models below.

First of all, the above optimization problem requires a knowledge of the cost functions $c_{i\ell}$. For fine examples of how such functions can be constructed, the reader is referred to Pathak, and Kühner [6]. Also, the Wharton study [7] demonstrates how point estimates or average costs can be obtained. The latter can be used to construct

linear cost functions. As Pathak [5] has shown, many of the functions $c_{i\ell}$ reflect economies-of-scale. However, economies-of-scale are usually due to capital costs; but this first simple model is essentially an "operating cost" model since the technology types are assumed to already be installed at the various locations, and therefore economies-of-scale may not be an issue here. However, for the next model we will return to a brief discussion of economies-of-scale.

If the cost functions $c_{i\ell}$ are convex (and therefore there are diseconomies-of-scale in operation) and if the pollution functions $P_{i\ell}$ are also convex, there are many high-speed algorithms which can readily solve for c(w). This means that for a region of established technologies at various locations, it is a somewhat routine matter to compute c(w) for many values, if one so chooses, of the vector w. Also, if the functions $c_{i\ell}$ and $P_{i\ell}$ are convex, it can be shown that c(w) is a convex function of the vector w and therefore there would be regional diseconomies-of-scale in operation.

If, in fact, some of the functions $c_{i\ell}$ or $P_{i\ell}$ are not convex (this is the case in the expansion model to follow), then the regional cost function c(w) is not easy to characterize, nor is it generally a simple task to compute c(w). In this latter case, one may have to resort to some "linearization" of the nonconvex functions in order to compute an "estimate" of c(w). Generally speaking, the worse the nonconvexity, the worse the estimate will be.

STEADY-STATE COST MODEL 2: TREATMENT CAPACITY EXPANSION

In this section we present an idealized steady-state (or static) optimization model for the purpose of computing c(w). For simplicity, we assume the region has no current treatment capacity (an assumption easily removed) and the vector w of solid wastes is an exogenous parameter. Therefore, the I waste types and the J waste generation locations are known. Also, there is a set of L locations at which waste treatment and disposal technologies may be located.

For simplicity, we proceed as follows: Assume there are T technology types, indexed t = 1,..,T, that can be utilized or installed at a given location ℓ. Also, we assume at most one technology type can be installed at a fixed location (this assumption is easily relaxed). Let $c_{it\ell}$ denote the capital and operating cost function for treating waste type i under technology type t at location ℓ. Also, we assume the waste loading vector w is known. Therefore, the cost of treatment of waste type i at location ℓ under technology type t is given by

$$c_{it\ell}\left(\sum_{j=1}^{J} \alpha_{ij\ell} w_{ij}\right) \quad . \tag{19}$$

Let $x_{t\ell}$ be a binary variable defined as follows: $x_{t\ell} = 1$ if technology type t is located at ℓ, and $x_{t\ell} = 0$ if technology type t is not located at ℓ. The constraints that no more than one technology type can be installed at any location ℓ are expressed as

$$\sum_{t=1}^{T} x_{t\ell} \leq 1, \quad \ell = 1,..,L \quad . \tag{20}$$

We also need some constraints which will not allow wastes to be sent to a location ℓ at which there is to be no installation. This is accomplished as follows. Let y_{ℓ} be defined as

$$y_{\ell} = \sum_{t=1}^{T} x_{t\ell} \quad . \tag{21}$$

Therefore, y_{ℓ} will be one or zero depending respectively on whether or not there is an installation at location ℓ. Then the constraints

$$\sum_{j=1}^{J} \alpha_{ij\ell} w_{ij} - y_{\ell}\, u_{ij} \leq 0, \quad i = 1,..,I, \ \ell = 1,..,L \tag{22}$$

guarantee that no waste will be sent to a location where there is no

treatment and disposal facilities.

The optimization problem for computing c(w) is then

$$c(w) = \underset{\alpha,\, x,\, y}{\text{minimize}} \sum_{\ell=1}^{L} \sum_{i=1}^{I} \sum_{t=1}^{T} x_{t\ell} c_{it\ell} \left(\sum_{j=1}^{J} \alpha_{ij\ell} w_{ij} \right)$$

$$\text{subject to} \quad \sum_{\ell=1}^{L} \alpha_{ij\ell} = 1, \; i = 1,..,I, \; j = 1,..,J$$

$$\sum_{t=1}^{T} x_{t\ell} \leq 1, \; \ell = 1,.., \qquad (23)$$

$$\sum_{t=1}^{T} x_{t\ell} - y_{\ell} = 0, \; \ell = 1,..,L$$

$$\sum_{j=1}^{J} \alpha_{ij\ell} w_{ij} - y_{\ell} u_{ij} \leq 0, \; i = 1,..I, \; \ell = 1,..,L$$

$$P_{i\ell} \left(\sum_{j=1}^{J} \alpha_{ij\ell} w_{ij} \right) \leq \bar{P}_{i\ell}, \; i = 1,..1, \; \ell = 1,..,L$$

$$\alpha_{ij\ell} \geq 0, \text{ all } i, j, \ell$$

$$x_{t\ell} = 0 \text{ or } 1 \quad , \quad t = 1,..T, \; \ell = 1,..,L$$

$$y_{\ell} = 0 \text{ or } 1 \quad , \quad \ell = 1,..,L$$

The above optimization problem reveals some important facts about the regional cost function c(w). In the first place it is quite likely that the functions $c_{it\ell}$ exhibit significant economies-of-scale[5,6]. Therefore, the above optimization problem is a mixed-integer nonlinear optimization problem where, in particular, the objective function is composed of concave parts. As such, it is almost impossible to characterize the nature of c(w), and it is also a generally difficult problem to solve such a problem. However, under separability, Pathak[5] has shown how such problems can be

approached by the branch and bound algorithm of Falk and Soland [8], and Kühner uses a commercially available mixed integer programming code. Therefore, in principle, c(w) can be computed, but it would be somewhat computationally expensive to carry out this operation for many values of the vector w. It is also safe to assert that the function c(w) has few of the characteristics of cost functions typically encountered in economics' usage.

There are many modifications of the above model that are valid in various contexts. However, the above model does capture the essence of the problem and the modifications are best carried out under particular computational situations.

It should also be pointed out that such models often lead to somewhat unexpected answers. For instance, Pathak found that pyrolysis, as well as land fill, appeared at a significant level in his optimal solutions. However, as he points out, such results also depend heavily on the rather tentative cost and air pollution data currently available for this technique.

It should be pointed out that the above model can easily be modified to handle the case where revenues are also earned from the recovery of certain solid waste constituents (e.g., ferrous metals) from the entire supply of solid wastes offered for disposal services. One merely needs to (i) add variables which account for the amount of various constituents recovered, (ii) include revenue terms in the objective function, and (iii) add mass balance type constraints which indicate the amount of a constituent recovered plus the amount disposed of must equal the total amount offered for disposal services. The reader is referred to Pathak [5] and Kühner [6] for detailed examples.

DYNAMIC COST MODEL

The dynamic or time-varying version of the above expansion model is quite easy to formalize. In particular, a time subscript,

$n = 1, 2, .., N$, is introduced on all functions and decision variables. Also, the objective function would contain appropriately discounted costs. Therefore, given the time varying vectors of wastes, w^n, the dynamic model is precisely of the same form as the steady-state expansion model. However, if N is large, then the number of integer variables significantly increases, and therefore such nonlinear mixed-integer programming problems may become costly to execute, especially if detailed sensitivity analyes (e.g., sensitivity analyses on w) are required.

SECTION V

THE BENEFIT MEASURE FOR SOLID WASTE POLICY DECISION

Effective government intervention in any sphere of economic activity must be based on a comparison of the benefits and losses associated with various alternative policies. Such, of course, must also be the basis of efforts to control the materials' cycles generating solid wastes. The benefits associated with intervention to control solid waste are the reduced disposal costs facing municipalities. These savings can be calculated for alternative policies through the "generation" and "disposal" models of the previous sections. The reduction in demand for disposal services that is the source of the savings, however, also results in a contraction of the productive potential of the economy. This is translated to consumers generally in the form of higher prices or reduced income. What constitutes an appropriate measure of this reduction in welfare is a difficult question that is yet to be completely resolved.

Almost universally the various welfare measures that have been recommended are based on their ultimate effects on consumers, usually measured as a monetary evaluation of changes in levels of utility. It should be noted in particular that this does not mean that effects on business are to be ignored. On the contrary, effects on business profits and levels of production are extremely important; but their importance is derived not from any intrinsic value, but from the value they ultimately provide to the citizens of the society - the consumers. Thus high profits ceteris paribus represent increased income to individuals. Similarly, increased output, ceteris paribus, represents increased welfare because it ultimately represents increased consumption by individuals. Thus, although welfare measures (sometimes referred to as benefit measures) are in the final analysis based on benefits to the individuals who compose society, effects on the

production sector of the economy are not ignored. Indeed, frequently in a partial equilibrium analysis, profits are specifically included in the measure.

EQUIVALENT VARIATION

Traditionally, economists have relied on the consumer's surplus measure or on one of its many variants. In this report we will rely on the equivalent variation as approximated by the more common "area under the demand curve" measure of consumer's surplus. Loosely, the equivalent variation may be thought of as the amount of income an individual would forego in order to avoid a specific change in prices. More formally, let the individual's utility function be given by

$$u = u(x_1,..,x_n) \tag{24}$$

where $x_1,..,x_n$ represent the amounts of commodities 1 through n consumed. Taking the prices and level of income, $(\vec{p}, m)$, as exogenous factors, the individual's n demand functions can be represented as

$$x_i(\vec{p},m) \qquad i = 1, 2,..,n \tag{25}$$

Substituting into the utility function gives

$$u = u(x_1(\vec{p},m),..,x_n(\vec{p},m)) = F(\vec{p},m), \tag{26}$$

the indirect utility function. If we let $\vec{p}^{o}$ and m^{o} represent the initial price vector and income respectively, and $\vec{p}^{1}$ represent the new vector of prices, the equivalent variation is defined as E where

$$F(\vec{p}^{o}, m^{o} + E) = F(\vec{p}^{1}, m^{o}) \tag{27}$$

The equivalent variation E is then the change in income at base prices necessary to make the individual indifferent to the new price vector. This measure is particularly appropriate because it allows the welfare effects of various policies to be converted into a money measure and compared. Unfortunately, it is impossible (except under very special circumstances) to calculate the value of E from observed market variables. For this reason, economists have traditionally chosen to use the more common consumer's surplus as measured by the area under the demand curve. Under certain circumstances, this may, in fact, be

an acceptable approximation. It is, however, important that the precise nature of this variant of consumer's surplus and its weaknesses be fully understood in order to recognize situations that require a more sophisticated treatment.

Recall, that a demand curve for a good i is a function $D_i^{-1}(q_i)$ that for each quantity of consumption q_i specifies the maximum price per unit that the consumer would be willing to pay, given that all units can be purchased at that price. Thus each point on an individual's demand curve represents the marginal or incremental value of the corresponding last unit. Summing up these incremental values and subtracting the amount actually paid provides the usual measure of consumer's surplus. Graphically, this is depicted in Figure 1 as the shaded area between the price line and the demand curve. Mathematically, this is expressed as

$$\int_0^{q_i^o} (D_i^{-1}(q_i) - p_i^o)dq_i \tag{28}$$

where

$$q_i^o = D_i(p_i^o) \tag{29}$$

The welfare effects, as measured by consumer's surplus, associated with a change in price from p_i^o to p_i^1 is that given by the shaded area in Figure 2 . Mathematically, this loss is just

$$q_i^1(p_i^1 - p_i^o) + \int_{q_i^1}^{q_i^o} (D_i^{-1}(q_i) - p_i^o)dq_i \tag{30}$$

where

$$q_i^o = D(p_i^o) \text{ and } q_i^1 = D(p_i^1) \tag{31}$$

Notice that this loss is conveniently divided into two parts: the additional money paid for the q_i^1 units consumed after the price change, plus a monetary evaluation of the loss in benefits from the

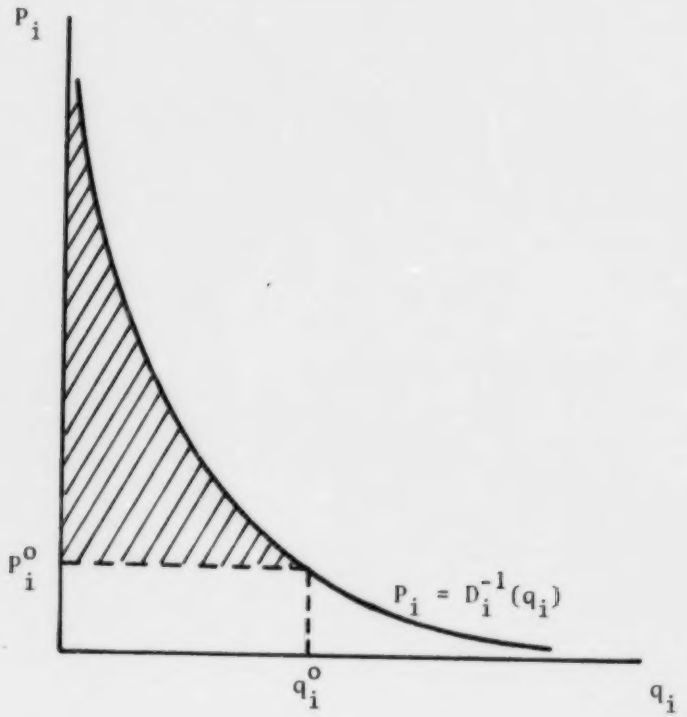

Figure 1 . Consumer's surplus

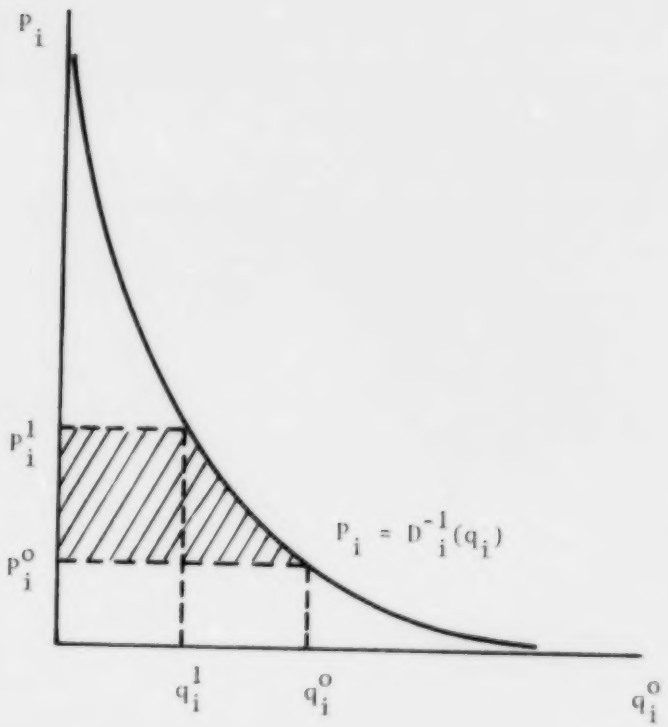

Figure 2. Consumer's surplus welfare effects due to a price change

reduced consumption

Similarly, the equivalent variation measure can be divided into two terms: the amount $q_i^1(p_i^1 - p_i^o)$ that would be paid to avoid the increased cost of the first q_i^1 units and the amount that would be paid to avoid having to reduce consumption. But the first term in the equivalent variation is just the same as the first term in the consumer's surplus measure. Thus to the extent that the two measures differ, it is in the monetary evaluation placed on the reduction in consumption. The difference results from a slight difference in the conceptual experiments on which each is based. The monetary evaluation on each unit in the consumer's surplus measure represents the amount that would be paid for one more unit of output, assuming that all the other units could be purchased at the same price. In the equivalent variation measure, the monetary evaluation on each additional unit is the amount that would be paid for one more unit of output, assuming that all other units are paid for at their marginal evaluation. In essence then the experiments are the same except that the equivalent variation bases the evaluation at each q_i on preferences resulting from utility maximization when the individual is assumed endowed with less wealth than in the case of consumer's surplus. Consequently, if the good under consideration is superior, the estimated evaluations are less than the corresponding evaluation in the case of consumer's surplus. Thus the more common consumer's surplus measure is an over estimate of the equivalent variation.

The question is under what circumstances is the common consumer's surplus measure a reasonably close approximation to the equivalent variation. The answer and much more is given by Robert Willig [9]. Let

$$A_i = \int_{p_i^o}^{p_i^1} D(p_i)\,dp_i \quad ,$$

$$a_i = \frac{A_i}{m^o} \quad , \tag{32}$$

and $\bar{\eta}_i$ and $\underline{\eta}_i$ be upper and lower bounds on the income elasticity of demand for q_i. That is

$$\bar{\eta}_i = \sup \left\{ \frac{\partial q_i(\vec{p}, m)}{\partial m} \Big/ \frac{m}{q_i(\vec{p}, m)} \; : \; \vec{p} \in \Gamma_i \;, \; m_o \leq m \leq u(\vec{p} | \vec{p}^o, m^o) \right\} \tag{33}$$

where

$$\Gamma_i = \left\{ p_1^o, \ldots, p_{i-1}^o, p_i, p_{i+1}^o, \ldots, p_n^o \; : \; p_i = (1-\lambda) p_i^o + \lambda p_i^1, 0 \leq \lambda \leq 1 \right\} \tag{34}$$

and $u(\vec{p} | \vec{p}^o, m^o)$ is that income with which the consumer facing prices p is just indifferent to the base situation represented by $(\vec{p}^o, m^o)$, and analogously for $\underline{\eta}_i$. Then it is shown by Willig that there exist bounds on the percent error $(A_i - E)/A_i$ in approximating the equivalent variation by A_i. The specific bounds depend on the value of $\bar{\eta}_i$ and $\underline{\eta}_i$. However, if $|a_i \bar{\eta}_i|$ and $|a_i \underline{\eta}_i|$ are small, then the error in the approximation is between $|a_i \bar{\eta}_i/2|$ and $|a_i \underline{\eta}_i/2|$. In most applications a_i should be very small since welfare effects in any case should be a small percentage of the income. Thus the usual consumer's surplus measure should be acceptable. Even if $|a_i \bar{\eta}_i|$ and $|a_i \underline{\eta}_i|$ are large but close in value, estimates can be made of E by multiplying the error by A_i and adding the result to the consumer's surplus measure.

If two or more prices are changing, consumer's surplus becomes a line integral, the value of which is in general dependent on the path of integration. The equivalent variation that is to be approximated is, however, uniquely defined independently of the path of price changes. In this case Willig [9] is able to show that the same results hold as in the one dimensional case, except that now $\bar{\eta}$ and $\underline{\eta}$ are interpreted as bounds on income elasticities for all goods with price changes, and A is the sum of the consumer surpluses where prices change sequentially. While A depends on the particular sequence of price changes assumed, the bounds hold independently

of which sequence is considered. For convenience, we adopt the following definition

$$A = \sum_{i=1}^{n} \int_{p_i^o}^{p_i^1} D_i(\vec{p}_i)\, dp_i \tag{35}$$

where

$$\vec{p}_i = (p_1^1, \ldots, p_{i-1}^1, p_i, p_{i+1}^o, \ldots, p_n^o) \quad . \tag{36}$$

The convention adopted is that the assumed path of integration is that path where prices change sequentially in the order indexed. The result holds for any renumbering of goods. The area A is shown in Figure 3 for n = 2.

Up to this point, the discussion has been in the framework of welfare effects on individuals. A meaningful measure requires that we aggregate over individuals. Let the K individuals be indexed by j and denote the change in consumer's surplus for individuals j by A^j, and let $D_i^j(\vec{p})$ be the demand function for the $i^{\underline{th}}$ good by individual j. Summing the individual consumer's surpluses gives

$$A = \sum_{j=1}^{K} A^j = \sum_{j=1}^{K} \sum_{i=1}^{n} \int_{p_i^o}^{p_i^1} D_i^j(\vec{p}_i)\, dp_i = \sum_{i=1}^{n} \int_{p_i^o}^{p_i^1} D_i(\vec{p}_i)\, dp_i \tag{37}$$

where

$$D_i(\vec{p}) = \sum_{j=1}^{K} D_i^j(\vec{p}) \tag{38}$$

is the market demand curve. The bounds on the percent degree of accuracy are now given by

$$\sum_{j=1}^{K} \left(A^j \Big/ A \right) \overline{B}^j \quad \text{and} \quad \sum_{j=1}^{K} \left(A^j \Big/ A \right) \underline{B}^j \tag{39}$$

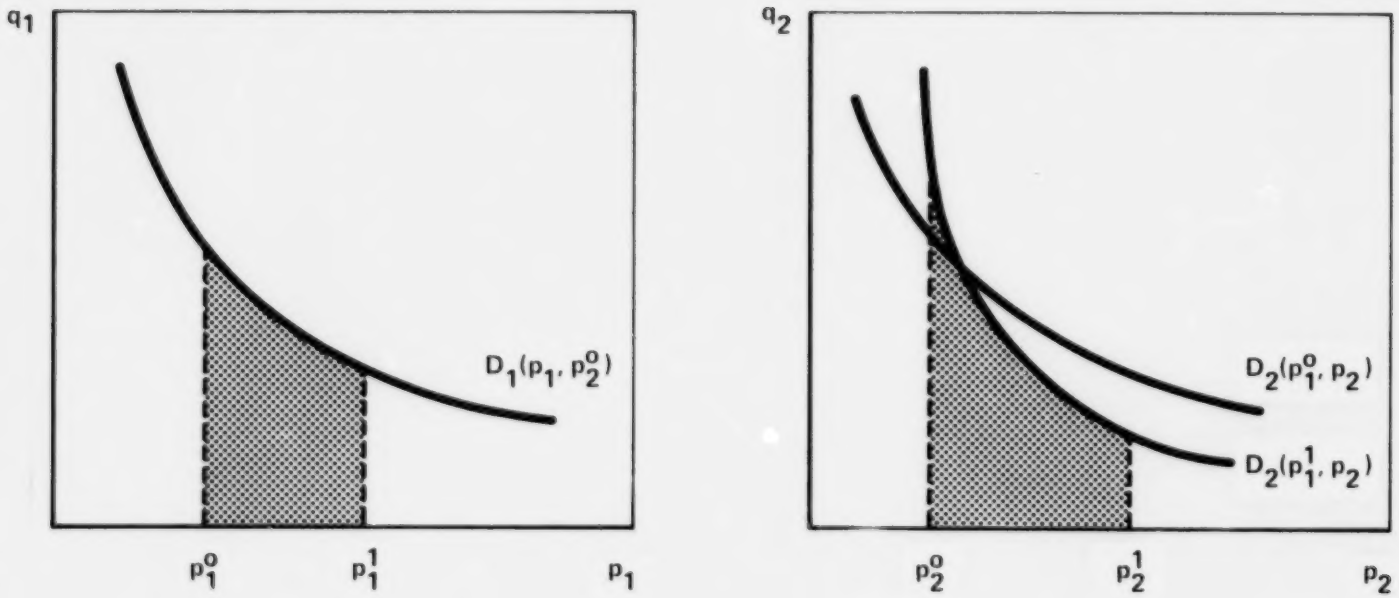

Figure 3. Two Dimensional Consumers' Surplus Approximation to Equivalent Variation.

where $\bar{B}^j$ and $\underline{B}_j$ are the upper and lower bounds on the percent error in the use of A^j to approximate the equivalent variation for individual j. Thus the bounds in the aggregate case are just the weighted averages of individual bounds.

THE BENEFIT MEASURE

It should be noted now that even an accurate measure of the equivalent variation would not capture all the welfare effects of government policy. This is because the equivalent variation implicitly takes individual income as given. In general, such will not be the case for industry profits (and hence will not be the case for returns to individuals on investments). The final measure, therefore, of welfare loss should also reflect the changes in industry profits and government revenue. Thus, the appropriate measure of welfare loss to use when considering, say, a policy P which results in a vector price change from p^o to $p^1 (= p(P))$ should include loss of profits and the change in government revenue as well as the consumers' surplus approximation to the equivalent variation. That is, welfare loss due to policy P is given by

$$S(p^o,p^1) = \sum_{i=1}^{n} \int_{p_i^o}^{p_i^1} D_i(\vec{p}_i)\,dp_i + \pi^o - \pi(P) + T^o - T(P) , \qquad (40)$$

where $p^1 = p(P)$ is the final vector of prices as a function of the policy P, π^o and T^o are the initial levels of profits and taxes respectively, and $\pi(P)$ and $T(P)$ are the final levels, respectively, of profits and taxes after the imposition of the policy P.

Now, $S(p^o,p(P))$ represents total welfare loss due to policy P. However, there is, presumably, a societal gain in the savings in waste disposal costs (i.e., we are, of course, assuming that the policy is implemented in order to have society re-evaluate its waste disposal decisions). Let $\bar{w}(p)$ represent the vector of solid wastes offered for disposal when the consumer goods price vector is p. Then the resulting savings in waste

disposal costs, due to policy P, is given by $c(\bar{w}(p^o)) - c(\bar{w}(p(P)))$ where $c(\bar{w})$ is the solid waste disposal cost function developed in Section IV . Therefore, the net welfare loss to society due to policy P is

$$B(p^o,p(P)) = S(p^o,p(P)) + c(\bar{w}(p(P))) - c(\bar{w}(p^o)) \quad . \tag{41}$$

Some remarks about the net welfare loss $B(p^o,p(P))$ are in order. It is clear that virtually any policy (e.g., taxes, subsidies, quantity constraints) will ultimately lead to a price change for consumer goods as well as to a change in solid waste disposal costs, and these terms must be weighed, one against the other, in order to determine whether or not a given policy is even potentially appropriate. Of course, major problems include knowing what the resulting new price vector p^1 will be and knowing the solid waste response vector $\bar{w}(p)$ in order to compute net welfare loss. For instance, if it is decided to tax, say, certain solid waste producing factors of production, then one must know how consumer goods prices will change as a function of the new taxes in order to compute optimal levels of the latter (such policies are fully discussed in Section VI).

For example, suppose it is decided to place excise taxes (possibly negative) on n consumer goods. Let $\tau = (\tau_1,..,\tau_n)$ denote the tax vector and let $p(\tau) = (p_1(\tau),..,p_n(\tau))$ denote the resulting consumer goods price vector. Also, let p^o, w^o be, respectively, the initial vectors of consumer goods prices and solid waste disposal levels. Then within the context of only considering taxes upon the n consumer goods, an optimal tax vector, τ^*, is found by solving

$$\underset{\tau}{\text{minimize}}\ S(p^o,p(\tau)) - c(w^o) + c(w(p(\tau))). \tag{42}$$

Naturally, the response vector function $p(\tau)$ and $w(p(\tau))$ may be quite difficult to obain in some applications. The latter, together with the need to estimate the demand and cost functions, makes the above optimization problem somewhat difficult to solve. Section VI explicitly deals with these problems in various taxation contexts.

THE BENEFIT MEASURE UNDER INDEPENDENCE

At this point it is worthwhile to show the relationship of the benefit measure (42) to the more common consumer surplus. Suppose that $\pi^o - \pi(P)$ and $T^o - T(P)$ (where the policy P is a tax on consumer goods) are completely represented by the change in profit of firms producing consumer goods and the change in tax revenues from the markets for consumer goods respectively. Finally, assume D_i depends only upon p_i, and C_i (the $i^{\underline{th}}$ consumer good production cost function) depends only upon the level of production of consumer good i. Then, for each i = 1,..,n

$$\int_{p_i^o}^{P_i(P)} D_i(p_i)dp_i = p_i(P)D_i(p_i(P)) - p_i^o D_i(p_i^o) - \int_{D_i(p_i^o)}^{D_i(p_i(P))} D_i^{-1}(u_i)du_i \quad (43)$$

and therefore, since

$$\pi^o - \pi(P) + T^o - T(P) = \sum_{i=1}^{n} \left[p_i^o D_i(p_i^o) - C_i(D_i(p_i^o)) - p_i(P)D_i(p_i(P)) + C_i(D_i(p_i(P))) \right] , \quad (44)$$

$$B(p^o, p(P)) = - \sum_{i=1}^{n} \left[\int_0^{D_i(p_i(P))} D_i^{-1}(u_i)du_i - C_i(D_i(p_i(P))) \right] \quad (45)$$

$$+ c(\bar{w}(p(P))) + \sum_{i=1}^{n} \left[\int_0^{D_i(p_i^o)} D_i^{-1}(u_i)du_i - C_i(D_i(p_i)) \right] - c(\bar{w}Op^o)) .$$

Making the substitution $q = D_i(p_i)$, we see that

$$B(p^o,p(P)) = -\sum_{i=1}^{n}\int_{o}^{q_i(P)}[D_i^{-1}(u_i) - S_i^{-1}(u_i)]du_i + c(w(q(P))) \tag{46}$$

$$+\sum_{i=1}^{n}\int_{o}^{q_i^o}[D_i^{-1}(u_i) - S_i^{-1}(u_i)]du_i - c(w(q^o)) \quad ,$$

where $w(q) = \bar{w}(D_1^{-1}(q_1),..,D_n^{-1}(q_n))$ and $S_i^{-1} = C_i'$.

That is, net welfare loss is the negative of the sum of consumers plus producers surpluses (evaluated at $q(P)$) minus solid waste disposal costs (evaluated at $q(P)$) plus a constant (evaluated at q^o) .

Therefore, under the assumption of independence of the demands for the n consumer goods and the assumption stated above about the nature of $\pi^o - \pi(P) + T^o - T(P)$, the taxing problem, discussed above,

$$\underset{\tau}{\text{minimize}} \quad B(p^o, p(\tau)) \tag{47}$$

is equivalent to the problem

$$\underset{\tau}{\text{maximize}} \quad \sum_{i=1}^{n}\int_{o}^{q_i(\tau_i)}[D_i^{-1}(u_i) - S_i^{-1}(u_i)]du_i - c(w(q(\tau))), \tag{48}$$

where $q_i(\tau_i) = D_i(p_i(\tau_i))$, $i = 1,..n$.

Of course, this latter problem is to choose τ^* so as to maximize the sum of consumers plus producers surpluses minus the resulting waste disposal costs.

SECTION VI
SOLID WASTE TAXING MODELS

The basic problem of economic efficiency in solid waste services is that for the most part such services are treated as a free good since the costs of collection and disposal are hidden in various taxes that are independent of the quantities of solid waste offered for collection by individual firms and households. The situation is formally analogous to the traditional problem of externality where there is either over or under production of some goods (usually joint products like smoke in steel production) because a market fails to exist which would reflect the true costs or benefits of the good in question. Economists have traditionally advocated the use of taxes or subsidies to reflect the relevant marginal costs or benefits. The value of such an approach rests on the fact that such taxes or subsidies when set appropriately cause the economy to function as if competitive markets exist for all goods. In the specific case of solid waste, since there is no market in disposal services, there is overproduction of such wastes by firms and households. The introduction of a tax would encourage both firms and households to reduce their rates of generation of solid waste for disposal.

Firms would tend to substitute other inputs for solid waste disposal services. Households would tend to switch to consumer goods that are less solid waste intensive. Both firms and households would have an incentive to utilize alternative methods of disposal; in particular, recycling would be strongly encouraged. There are, however, possible difficulties in the use of solid waste taxes in that while they will tend to reduce the rate of generation of solid waste, they may result in increased use of other undesirable methods of disposal (e.g., incineration and littering). These problems along with the difficulties introduced by monopolistic production are special cases of the general theory of the second best which will be discussed more fully later in this Section.

In this section we develop models for studying the taxation of consumer products and factors of production in order to control some characteristics of the solid waste stream. The models determine the optimal tax levels, where optimality is defined in terms of specific benefit measures based upon the theory developed in Section V.

The taxing models are intended to be applicable institutionally to a mixed economy such as that in the U.S. and most Western economies in which profit-maximizing firms and utility-maximizing individuals control most or all production and the supply of productive inputs, while solid waste collection, processing and disposal are controlled directly by a Central Solid Waste Authority (SWA). Production and factor services that give rise to solid waste are only indirectly controlled by the SWA through taxes that it can levy on certain commodities. For the first set of models, the SWA is assumed to optimize net benefits related to the consumption of final output subject to certain constraints required by the economic relations of the private sector of the economy. Thus, these taxes are intended to <u>decentralize</u> the functioning of the economy in the sense that when taxes of the magnitude determined by the model are actually imposed (assuming the SWA has correctly estimated firms' responses), private firms are induced to achieve precisely those levels of production that in fact yield the optimum level of benefits.

Another way of describing the analytic framework is that we are considering situations of the "second best" where we are willing to tolerate monopolistic behavior on the part of certain firms that reduce output, and hence benefits, but that we may, in part, attempt to correct such behavior. In the set of models, the prices of consumer goods are the decision variables. However, the resulting optimal prices are not to be enforced, but rather they are used to compute the optimal taxes which, if enforced, will lead the private sector to produce those quantities of consumer goods which, in fact, optimize net benefits. That is, the optimal prices of consumption goods is used only as an intermediate step by which the SWA can compute optimal taxes.

These models are formulated in terms of observable market relations, as opposed to the usual taxing models which are couched in terms of individual utility functions and/or social welfare functions which are very difficult to measure. These observable functions include market demand and supply curves, monopolistic firms' production cost functions, and solid waste "production functions," all of which can be econometrically measured.

The models also allow the Authority choice of the various levels in the different materials production cycles at which to intervene in markets (i.e., levy taxes). The main reason for considering many decision points (sectors) of production and consumption at which to intervene with taxes is that even though the apparent "level" at which to tax is at the solid waste disposing level, policy instruments at other levels provide us with a more flexible (theoretically) model and hence if such taxes can be computed (or iteratively arrived at), the net benefits to society will be greater than if taxes are only imposed upon solid waste itself. However, as we shall see later on, the taxing of only solid waste itself has many advantages from an operational point-of-view, and such a procedure falls closely in line with the usual economic thinking about such matters.

To fix understanding of the structure of the models and how they are intended to function, we first present a simple model in which taxes are levied only at the consumer goods level. This model does not adequately deal with possible factor substitution among solid waste producing materials. We then formulate a more general version of the model in which taxes on factors of different types are included. The second version includes these substitution effects in production and allows intervention by taxation on factor inputs.

The models that follow can be interpreted as operating under static or steady-state conditions. Dynamic models require specification of investment relations, demand growth and technological change, which are difficult to anticipate and for some aspects too difficult to adequately model. Dynamic aspects, however, will be touched upon

in other places below.

TAXES ON CONSUMER GOODS

Let $q_i = D_i(p)$, $i = 1,..,n$, be the level of output of consumer good i, where $p = (p_1,..,p_n)$ is the vector of prices of goods $q = (q_1,.., q_n)$. That is, $D_i(p)$ is the demand function for good i as a function of all n consumer good prices. Let $\tau = (\tau_1,..,\tau_n)$ be the vector of taxes to be imposed upon the n consumer goods and let $p(\tau) = (p_1(\tau),..,p_n(\tau))$ denote the consumer good price response vector as a function of the vector of consumer goods taxes τ. It should be emphasized that $p(\tau)$ is, in fact, the equilibrium price vector for consumer goods when a tax vector of τ has been imposed and hence should be thought of as the solution to the usual tâtonnement fixed point problem.

As in Section V, the problem the SWA must solve in order to find an optimal tax vector τ^* is

$$\underset{\tau}{\text{minimize}}\ S(p^o, p(\tau)) + c(\bar{w}(p(\tau))) - c(w^o), \tag{49}$$

where $p^o = (p_1^o,..,p_n^o)$ is the exante tax consumer good price vector, w^o is the exante tax solid waste production, and $c(\bar{w})$ is the SWA's solid waste disposal cost function developed in Section IV. Therefore, $\bar{w}(p(\tau))$ is the solid waste response as a function of the tax vector τ. At this point it is worthwile to spell out the intracacies in the above problem that are, perhaps, camouflaged by the notation. The above optimization problem can be rewritten (see Section V) as

$$\underset{\tau}{\text{minimize}} \sum_{i=1}^{n} \left[\int_{p_i^o}^{p_i(\tau)} D_i(\vec{p}_i(\tau))dz_i + p_i^o D_i(p^o) - C_i(D_i(p^o)) - p_i(\tau)D_i(p(\tau)) + C_i(D_i(p(\tau))) \right] + c(\bar{w}(p(\tau))), \tag{50}$$

where we have dropped the constant $- c(w^o)$, and

$$\vec{p}_i(\tau) = (p_1(\tau),..,p_{i-1}(\tau), z_i, p_{i+1}^o,..,p_n^o),\ i = 1,..,n. \tag{51}$$

We have also assumed that the term $\pi^o - \pi(\tau) + T^o - T(\tau)$ is completely represented by the change in profits of firms producing the final outputs and the change in tax revenue from the markets for the final outputs.

The gross benefits measure is composed by consumer demand functions since the assumption is that societal welfare is a function of utility levels of consumers only. Thus, in the case of goods used both by consumers and producers it becomes necessary to isolate, if possible, the consumer component of that demand. Similarly, the cost functions must be separated into components based on the quantities going into factor markets and consumption markets.

All the joint demand functions $D_i(p)$, $i = 1,..,n$, must be estimated and similarly for all the production cost functions $C_i(q_i)$, $i = 1,..,n$. For competitive industries C_i' is, of course, the supply function for that industry and is the sum of the marginal cost functions of the firms of that industry. For simplicity and because of inadequate theory oligopolistic (and oligopsonistic) industries are not meant to be included in the taxing model. However, the model could easily handle oligopolistic industries if the behavioral rules whereby the prices and quantities of each member of the industry are determined can be specified (e.g., see Cyert and March [10] who discuss some simple behavioral models). In some cases then one can treat an oligopolistic industry as a monopoly (or a competitive industry) by aggregating the firms together into a single monopolistic firm and abstracting from their intra-industry adjustments.

We now come to the informational requirement which is, perhaps, the greatest in the above model. The vector $p(\tau)$ is the equilibrium response vector of consumer goods prices as a function of the consumer goods tax vector τ. Therefore, in order to know $p(\tau)$, the SWA must know how all consumer goods markets in question readjust when consumer goods taxes are imposed. Naturally, the need (in the context of the model under discussion) to know these equilibrium response functions is that if they are not considered and taxes are imposed by some other means, then such taxes will not decentralize the economy. That is, it will generally not be the case that firms and consumers will act in the manner desired.

Therefore, assume each consumer good q_i, $i = 1,..,n$, is either produced competitively or monopolistically. Let I_c be the set of indices corresponding to competitively produced consumer goods and let I_m be the set of indices corresponding to monopolistically produced consumer goods. Therefore we are assuming $I_c \cup I_m = \{1,2,..,n\}$ and $I_c \cap I_m = \phi$. Now, if a tax vector $\tau = (\tau_1,..,\tau_n)$ is imposed upon consumer goods, then the tax vector τ must satisfy

$$\tau_i = \begin{cases} p_i(\tau) - C_i'(D_i(p(\tau))) & , \quad i \in I_c \\ p_i(\tau) + D_i(p(\tau)) \Big/ \dfrac{\partial D_i(p(\tau))}{\partial p_i} - C_i'(D_i(p(\tau))), & i \in I_m \end{cases} \tag{52}$$

That is, τ_i must equal the difference between marginal revenue and marginal cost for each of the consumer goods markets where these quantities are, of course, for equilibrium quantities consistent with the price vector $p(\tau)$.

Another important data input which the SWA must know is the solid waste response vector $\bar{w}(p(\tau))$ as a function of the tax vector τ. It is at this point that we see that the model is not as theoretically sharp as we may wish (this will be alleviated below). The reason is that while solid waste constituents may be statistically related to consumer goods production, it is generally not the case that solid waste production depends only upon the level of production. In particular, a great deal of solid waste potential is related to factors of production rather than to level of production. However, setting this latter point aside for the moment we see that the SWA will need to obtain estimates of solid waste production as a function of levels of production of consumer goods. In this context a simple model for $\bar{w}(p(\tau))$ is as follows. Assume there are I types of wastes and let A be an Ixn matrix where $a_{k\ell}$ is the total amount of waste type k offered for solid waste disposal due to one unit of production of consumer good ℓ. Then letting $D(p(\tau)) = (D_1(p(\tau)),.., D_n(p(\tau)))$, the vector of solid wastes offered for disposal, as a

function of the tax vector τ, is given by the matrix-vector product

$$\bar{w}(p(\tau)) = A\, D(p(\tau)). \tag{53}$$

Now, knowledge of the equilibrium response vector, $p(\tau)$ is essentially contained in knowledge of D_i and C_i, $i = 1,..,n$. That is, to find an optimal tax vector τ^* one need only solve the optimization problem using p as the decision vector. Once an optimal vector of consumer goods prices, p^*, is found one then uses the marginal revenue minus marginal cost rule (evaluated at p^*) to find τ^*. In particular, p^* is found by solving the problem

$$\underset{p}{\text{minimize}} \sum_{i=1}^{n} \left[\int_{p_i^o}^{p_i} D_i(\vec{p}_i)dz_i + p_i^o D_i(p^o) - C_i(D_i(p^o)) - p_i D_i(p) + C_i(D_i(p)) \right] + c(\bar{w}(p)), \tag{54}$$

where $p = (p_1,..,p_n)$ and $\vec{p}_i = (p_1,..,p_{i-1}, z_i, p_{i+1}^o,..,p_n^o)$.

Once p^* is computed, τ^* is determined by equation (52) so that

$$\tau^* = \begin{cases} p_i^* - C_i'(D_i(p^*)) & , i \in I_c \\ p_i^* + D_i(p^*) \Big/ \dfrac{\partial D_i(p^*)}{\partial p_i} - C_i'(D_i(p^*)) & , i \in I_m \end{cases}. \tag{55}$$

That is, net loss in welfare is minimized with respect to consumer goods prices and then the market clearing mechanism is used to compute the associated optimal tax vector.

Note that in this formulation we have assumed that the i^{th} consumer good cost function depends only upon the level of production of that good and not of other consumer goods. In some applications this assumption may not hold since as consumer goods levels change, so do factor usage levels and hence so will factor price levels. If the latter change significantly, then the i^{th} cost function will

shift and therefore such cost functions do, in general, depend upon levels of production of other consumer goods which use similar factors of production. However, for our formal model this offers no problem since we can merely replace $C_i(D_i(p(\tau)))$ by $C_i(D(p(\tau)))$, where

$$D(p(\tau)) = (D_1(p(\tau)),\ D_2(p(\tau)),\ldots,D_n(p(\tau))) \ . \qquad (56)$$

Naturally, the latter replacement requires a greater amount of information on the part of the SWA. In particular, the SWA would have to know the response of factor markets to consumer goods taxes. We return to these problems when discussing factor taxation.

One final point to note is that there is nothing in the model to preclude negative taxes to certain consumer goods industries. In particular, it may occur that an optimal tax on a monopolistically produced good will be negative (note that the term "monopoly" is being used in the following sense: any firm facing a downward sloping demand curve for its product and which equates marginal cost and marginal revenue is called a monopoly). Of course, a negative tax will lead to greater waste production by that particular firm. The reason that such negative taxes may be optimal is that monopolists already restrict output to be below the socially desirable output level ("price equals marginal cost"), and benefits to society including the social costs to disposal may indeed be increased by having such a firm produce more of its output and hence more wastes. (For a detailed graphical treatment of this phenomena see Buchanan[11]. A mathematical derivation of the possibility of such negative taxes is to be found below on pages 55-58 . Also, a relevant discussion of "bribes" is contained in Kamien, Schwartz, and Dolbear[12].) Such negative taxes may be deemed objectionable on equity grounds. This perhaps could be avoided in part by putting limits on how negative a particular consumer good tax may become. On the other hand, the SWA could elect to ignore the social costs associated with monopolistic production under the rational that the Justice Department is the more appropriate agency to deal with this particular problem.

In order to discuss in more detail the above optimization problem for computing an optimal consumer goods tax vector, we introduce below a simplified version of the model. All the remarks about the nature of the simplified model carry over to the above model.

A SIMPLIFIED CONSUMER GOODS TAXING MODEL

For the sake of simplicity and, perhaps, greater operational usefulness in some situations, we make the following additional assumption. We assume all demand and cost functions are not joint. That is, the functions D_i and C_i depend only upon p_i and the level of production of the $i^{\underline{th}}$ good respectively. Then, as shown in Section V, the consumer goods taxing model becomes equivalent to

$$\underset{\tau}{\text{maximize}} \sum_{i=1}^{n} \int_{0}^{q_i(\tau_i)} D_i^{-1}(u_i)du_i - C_i(q_i(\tau_i)) - c(w(q)), \qquad (57)$$

where $q = (q_1,..,q_n)$, $w(q) = \bar{w}(D_1^{-1}(q_1),..,D_n^{-1}(q_n))$, and $q(\tau) = (q_1(\tau_1),..,q_n(\tau_n))$ is the equilibrium response vector of consumer goods levels as a function of the consumer goods tax vector τ. This problem is equivalent to the following problem:

$$\underset{q,\tau}{\text{maximize}} \sum_{i=1}^{n} \int_{0}^{q_i} D_i^{-1}(u_i)du_i - C_i(q_i) - c(w(q))$$

subject to

$$\begin{aligned} & D_i^{-1}(q_i) - C_i'(q_i) - \tau_i = 0 \quad , \quad i\in I_c \\ & D_i^{-1}(q_i) + \frac{dD_i^{-1}(q_i)}{dq_i} q_i - C_i'(q_i) - \tau_i = 0 \quad , \quad i\in I_m \\ & q_1, q_2,..,q_n \geq 0 \quad . \end{aligned} \qquad (58)$$

That is, we can optimize over the quantities of consumer goods to be produced and then use the market clearing mechanism to compute an

optimal tax vector. We again point out that the constraints indicate our desire to, in principle, compute taxes which will also decentralize the economy; that is, the imposition of an optimal tax vector will induce the production and consumption of the optimal vector of consumer goods.

It is in the above simplified form that the consumer goods taxing model is most useful. In particular, in many situations it may be that the number of consumer goods which leads to a great deal of some solid waste constituent (say newspapers or aluminum cans) is quite small. Also, in many situations it may additionally be the case that the corresponding demand or marginal cost functions depend upon relatively few other commodities (of course the latter points are empirical questions). Note however, that if it is hoped that commodity taxes on products packaged in, say, aluminum cans will lead to a reduction in the quantity of aluminum cans appearing for disposal services, then one must take care to also impose taxes upon commodities packaged in materials which are substitutes for aluminum cans. That is, if coke comes in bottles and aluminum cans, then identifying only coke in aluminum cans for commodity taxation will lead to more coke bottles appearing for solid waste disposal services and little will have been gained by imposing an excise tax on coke in aluminum cans.

In fact, it is for the above outlined reason that we find the notion of a "materials cycle" to be of somewhat limited use. Other materials may be capable of substitution for the particular material in question and therefore must be considered in analyses such as the one developed in this section. Of course, the notion of a "materials cycle" becomes much more useful in an assumed world of non substitution (e.g., see Kneese, et al.[1]). To further make the point, it seems clear that one cannot consider paper packaging materials without considering, say, plastic packaging materials and/or metal packaging materials such as, say, aluminum foil.

Therefore, to make the simple model above operational, one must isolate those major constituents of solid waste (e.g., paper) and

then consider those consumer goods which lead to a great deal of paper solid waste, and then consider all additional consumer goods which will act in a way to produce substitute solid waste for disposal services. It is the collection of all such consumer goods which must be considered for commodity taxation. (In what follows we use the notation $S_i^{-1} = C_i'$.)

Once such commodities are identified, it then becomes crucial to estimate the functions D_i^{-1} and S_i^{-1}, $i = 1,..,n$, for only then can the equilibrium response functions $q_i(\tau)$, $i = 1,..,n$, be estimated thereby allowing us to evaluate the gross benefits associated with the tax vector τ. Additionally, the SWA must have good estimates of the solid waste response vector $w(\tau)$ in order to compute the disposal cost $c(w(\tau))$ as discussed in Section IV . Of course, if the equilibrium response functions $q_i(\tau_i)$, $i = 1,..,n$, are well estimated and if solid waste generation as a function of consumer goods consumption is well understood, then automatically one has at hand the solid waste response vector $w(\tau)$ as a function of the tax vector τ . At this point we derive some interesting results about the optimal tax levels for the simplified model.

The Lagrangian function for the simplified consumer goods taxation model corresponding to problem (58) is

$$L(q,\tau,\lambda,\mu,\gamma) = \sum_{i=1}^{n} \int_0^{q_i} [D_i^{-1}(z_i) - S_i^{-1}(z_i)]dz_i$$

$$- c(w(q)) - \sum_{i\in I_c} \lambda_i (D_i^{-1}(q_i) - S_i^{-1}(q_i) - \tau_i) \tag{59}$$

$$- \sum_{i\in I_m} \mu_i (MR_i(q_i) - S_i^{-1}(q_i) - \tau_i) + \sum_{i=1}^{n} \gamma_i q_i \quad ,$$

where $\gamma_1,..,\gamma_n$ are nonnegative multipliers for the inequality constraints $q_i \geq 0$ for i=1,2,..,n, and $q=(q_1,..,q_n)$. Now let

$(q^*, \tau^*, \lambda^*, \mu^*, \gamma^*)$ be a Kuhn-Tucker point of the Lagrangian and let q^*, τ^* be optimal. Then from the first order conditions we must have for $i \in I_c$

$$D_i^{-1}(q_i^*) - S_i^{-1}(q_i^*) - \lambda_i^* \left[\frac{dD_i^{-1}(q_i^*)}{dq_i} - \frac{dS_i^{-1}(q_i^*)}{dq_i} \right]$$

$$- \sum_{j=1}^{I} \frac{\partial c(w(q^*))}{\partial w_j} \frac{\partial w_j(q^*)}{\partial q_i} = - \gamma_i^* \leq 0 \quad , \tag{60}$$

and for $i \in I_m$

$$D_i^{-1}(q_i^*) - S_i^*(q_i^*) - \mu_i^* \left[\frac{dMR_i(q_i^*)}{dq_i} - \frac{dS_i^{-1}(q_i^*)}{dq_i} \right]$$

$$- \sum_{j=1}^{I} \frac{\partial c(w(q^*))}{\partial w_j} \frac{\partial w_j(q^*)}{\partial q_i} = - \gamma_i^* \leq 0 \tag{61}$$

Now, under the assumption $q_i^* > 0$, $i = 1,..,n$, we have $\gamma_i^* = 0$, $i = 1,..,n$, and therefore both terms above on the left hand side of the two sets of inequalities are actually equal to zero. Note that if the Lagrangian is differentiated with respect to the variable τ_i then, since λ_i for $i \in I_c$ and μ_i for $i \in I_m$ are unrestricted in sign, we must have that $\lambda_i^* = 0$ for all $i \in I_c$ and $\mu_i^* = 0$ for all $i \in I_m$. Also, since we must have that $\tau_i^* = D_i^{-1}(q_i^*) - S_i^{-1}(q_i^*)$ for $i \in I_c$, we see that

$$\tau_i^* = \sum_{j=1}^{I} \frac{\partial c(w(q^*))}{\partial w_j} \frac{\partial w_j(q^*)}{\partial q_i} \quad , \quad i \in I_c \quad . \tag{62}$$

That is, for competitively produced consumer goods the optimal tax must equal the SWA's marginal cost of disposing of wastes due to an incremental change in the output level of consumer good i. Of course, this marginal cost depends upon the optimal production levels of all the n consumer goods (note that $\tau_i^* \geq 0$ for $i \in I_c$).

Since for $i \in I_m$ we have

$$MR_i(q_i) = \frac{dD_i^{-1}(q_i)}{dq_i} q_i + D_i^{-1}(q_i) , \tag{63}$$

and since an optimal tax must satisfy

$$\tau_i^* = MR_i(q_i^*) - S_i^{-1}(q_i^*) \quad , \tag{64}$$

the second set of inequalities above implies

$$\tau_i^* = \sum_{j=1}^{I} \frac{\partial c(w(q^*))}{\partial w_j} \frac{\partial w_j(q^*)}{\partial q_i} + \frac{dD_i^{-1}(q_i^*)}{dq_i} q_i^* \tag{65}$$

for $i \in I_m$. That is, the optimal tax for monopolistically produced consumer goods must equal the SWA's marginal cost (due to an incremental change in the consumer product output level) plus an additional term. Since we naturally assume downward sloping demand functions, we see that the additional term is negative. The implication is that if a competitively produced consumer good and a monopolistically produced consumer good are both imposing upon the SWA the same marginal waste disposal cost, the optimal tax upon the monopolistically produced good will be <u>smaller</u> than the optimal tax upon the competitively produced good. And, of course, depending on the relative absolute magnitudes of the two terms, the tax may in fact be negative as discussed on page 50 .

If there is significant joint dependence among the demand functions D_i, $i = 1,..,n$, then the optimization problem which uses the consumer goods price vector, p, as its decision vector is more difficult. However, it is worthwhile to point out that the above results regarding the taxation of competitively and monopolistically produced consumer goods essentially carry over to the case of joint dependence.

This optimization problem is

$$\underset{p}{\text{minimize}}\ B(p^o,p) = \underset{p}{\text{minimize}}\ \ S(p^o,p) + c(\bar{w}(p)) - c(\bar{w}(p^o)) \tag{66}$$

Let p^* denote an optimal consumer goods price vector and define the two vectors

$$\hat{p}_i^* = (p_1^*,\ldots,p_i^*,\ p_{i+1}^o,\ldots,p_n^o) \tag{67}$$

and

$$\vec{p}_i^* = (p_1^*,\ldots,p_{i-1}^*,z_i,p_{i+1}^o,\ldots,p_n^o) \quad . \tag{68}$$

Assuming the vector p^* has each of its components positive, we get (see page 46).

$$0 = \frac{\partial B(p^o,\ p^*)}{dp_i} = D_i(\vec{p}_i^*) + \sum_{k=i+1}^{n} \int_{p_k^o}^{p_k^*} \frac{\partial D_k(\vec{p}^*)}{\partial z_k}\, dz_k$$

$$- \sum_{k=1}^{n} \left[p_k^* - C_k'(D_k(p^*))\right] \frac{\partial D_k(p^*)}{\partial p_i} + c'(w(p^*)) \frac{\partial w(p^*)}{\partial p_i} \quad . \tag{69}$$

Now, for $i \in I_c$ we have $\tau_i^* = p_i^* - C_i'(D_i(p^*))$. Therefore, adding

$$\tau_i^* \frac{\partial D_i(p^*)}{\partial p_i} \tag{70}$$

to both sides of the above equality we get

$$\tau_i^* \frac{\partial D_i(p^*)}{\partial p_i} = D_i(\vec{p_i^*}) + \sum_{k=i+1}^{n} \int_{p_k^o}^{p_k^*} \frac{\partial D_k(\vec{p_k^*})}{\partial z_k} dz_k \tag{71}$$

$$- \sum_{\substack{k=1 \\ k \neq i}}^{n} [p_k^* - C_k'(D_k(p^*))] \frac{\partial D_k(p^*)}{\partial p_i} + c'(w(p^*)) \frac{\partial w(p^*)}{\partial}$$

Dividing this equality through by $\frac{\partial D_i(p^*)}{\partial p_i}$ yields τ_i^* for $i \in I_c$. Also, for $i \in I_m$ we have

$$\tau_i^* = p_i^* + D_i(p^*) \Big/ \frac{\partial D_i(p^*)}{\partial p_i} - C_i'(D_i(p^*)) \tag{72}$$

and therefore,

$$\tau_i^* \frac{\partial D_i(p^*)}{\partial p_i} = D_i(\vec{p_i^*}) + D_i(p^*) + \sum_{k=i+1}^{n} \int_{p_k^o}^{p_k^*} \frac{\partial D_k(\vec{p^*})}{\partial z_k} dz_k \tag{73}$$

$$- \sum_{\substack{k=1 \\ k \neq i}}^{n} [p_k^* - C_k'(D_k(p^*))] \frac{\partial D_k(p^*)}{\partial p_i} + c'(w(p^*)) \frac{\partial w(p^*)}{\partial p_i}$$

Dividing this latter equality through by

$$\frac{\partial D_i(p^*)}{\partial p_i} \tag{74}$$

yields τ_i^* for $i \in I_m$. Therefore, the expressions for the two cases are the same except that the expression for τ_i^*, $i \in I_c$, contains the additional negative term,

$$D_i(p^*) \Big/ \frac{\partial D_i(p^*)}{\partial p_i} \quad . \tag{75}$$

Therefore, ceteris paribus, a monopolistically produced consumer good's tax is smaller than that for competitively produced good. However, we cannot conclude (as we are able to for the simplified model) that the tax for a competitively produced consumer good is necessarily nonnegative.

As far as the computational feasibility of the simpler model is concerned, we wish to again point out the knowledge of D_i^{-1} , S_i^{-1}, $i = 1,..,n$, is required in order to understand equilibrium responses to taxes. Once this is known, and knowledge of solid waste response to changing consumer levels is obtained, then one has at hand the vector function $w(\tau)$. Therefore $c(w(\tau))$ can be obtained by the methods developed in Section IV. Once all the latter data are developed, the optimization (over q) may be relatively easy ; however, because of the likely nature of the SWA cost function (discussed in Section IV) as well as the nature of the integrand, the objective function is not necessarily concave in the decision variables $q_1,..,q_n$ and some relatively sophisticated search methods may be required.

On the other hand, the constraints can essentially be ignored since their role is merely to compute the optimal taxes once the optimal q's are known. Therefore, from an optimization view point, the simpler problem can be thought of as an unconstrained nonconcave maximization problem which, if n is not too large, might easily be solved to optimality. Note also that finding an exact optimal may not be necessary. That is, if a "good" q vector has been found then the taxes corresponding to the q vector also decentralize the economy.

Even in the simple model there is the problem of finding the unknown demand and supply functions, especially if there is a large stochastic or seasonal element. In the more complex case of dependent demands the informational as well as computational

requirements become unmanageable. An alternative approach that is deserving of consideration uses the ability of actual markets to compute equilibrium prices to reduce the information necessary for the implementation of optimal taxes.

Also, it is important to understand the shapes (concavities or nonconcavities) of the functions in question for another reason. Since we know the structure of optimal taxes τ^*, there is the possibility of using this structure to find, iteratively, an optimal tax vector without knowing the functions D_i^{-1} and S_i^{-1}, $i=1,..,n$. In particular, if q^o is the current consumption level, then define the initial consumption goods tax vector τ^o as follows. For $i\epsilon I_c$, let τ_i^o be the marginal cost, to the SWA, evaluated at q^o, and, for $i\epsilon I_m$, let τ_i^o be the marginal cost to the SWA (evaluated at q^o) plus the additional negative term

$$\frac{dD_i^{-1}(q_i^o)}{dq_i} q_i^o \quad . \tag{80}$$

We then (perhaps after some time) observe a new consumption vector, say, q^1 and we define a new tax vector τ^1. The procedure stops when a new tax vector leads to the same consumer goods vector as at the previous iteration. Such an iterative process is attractive since the information requirement is relatively low. That is, the SWA needs to know its own cost function and D_i^{-1} for $i\epsilon I_m$. However, because of the likely nature of the functions involved, there is not even a mathematical guarantee that such a procedure will lead to an optimal set of taxes. Also, there are strong practical reasons for perhaps not employing such a process. For instance, one would have to take care to be sure that an observed change in the consumer goods vector (or waste disposal vector) is actually due to the tax imposition and not to other reasons! Also, frequent changes in the tax vector may create such great uncertainties for producers so as to essentially invalidate the entire iterative process. For these reasons it is

perhaps better to obtain (at some expense) knowledge of the functions D_i^{-1} and S_i^{-1}, i = 1,..,n, and to actually compute an optimal tax vector and not change this obtained vector for a significant length of time. We will have more to say about these matters later on in this section.

TAXES ON CONSUMER GOODS AND FACTORS OF PRODUCTION

As pointed out above, in the section on consumer goods taxation, solid waste production is generally not merely a function of the levels of consumer goods production but also depends upon the manner in which these goods are produced (e.g., the factor mixes used). For instance, a product in a returnable container does not have the same solid waste impact as does the same product in a disposable container. Or, more generally, factors of production which are recyclable do not have the same solid waste potential as factors of production which are not recyclable Of course, factors of production also play an important role in other environmental problem areas. For instance, a given level of KWH is more air polluting if produced by high sulfur fuel than by low sulfur fuel. That is, from an air pollution point of view it would make more sense to concentrate on the manner in which a given level of KWH is produced than upon the level itself. As far as solid waste problems are concerned, it seems highly desirable that a general taxing model include the possibility of taxation of various factors of production of consumer goods. In particular, it may be highly beneficial to economically discourage, say, disposable aluminum cans and thereby encourage reusable aluminum cans or other reusable packaging materials. On the other hand, for solid waste items such as newspapers, magazines,and auto hulks, it seems apparent that taxing the waste itself is more likely to encourage markets for collection and recycling than will taxing the factors of production for such items. This seems obvious for newspapers and magazines since there is a strong correspondence between the product and one of its major factors of production, paper. That is, for newspapers and magazines a consumer goods excise tax and/or a waste disposal charge should suffice for the purpose of encouraging the practice of

recycling. We wish to point out that unsold newspapers and magazines are collected since there is positive economic value for the paper. On the other hand, sold newspapers create a much larger collection cost and there is generally little attempt made to make such collections. In the case of autos, because of the great time lag between purchase and ultimate disposal, a consumer goods tax seems pointless while a waste disposal or "abandonment fee" should work well, especially if a regional authority announced its willingness to accept auto hulks free of charge (or even at some positive value). We shall have more to say about such issues below in the section on solid waste disposal taxes.

We now return to a discussion of a model incorporating taxes upon factors of production as well as consumer goods taxes.

Recall, the general objective of the SWA in the case of consumer goods taxation is

$$\underset{\tau}{\text{minimize}}\ S(p^o,\ p(\tau)) + c(\bar{w}(p(\tau))) - c(\bar{w}(p^o)) \quad . \tag{81}$$

However, examination of the model indicates that the taxes can be placed upon anything as long as one is able to obtain estimates of the equilibrium price response vector $p(\tau)$ as a function of the tax vector τ as well as the solid waste response vector $\bar{w}(p(\tau))$. Also, in the consumer goods taxation model we assumed we can obtain estimates of the marginal cost functions S_i^{-1}, $i = 1, ..,n$. For a model which places taxes upon some factors of production it seems that the additional knowledge of production functions is required. While knowledge of the latter is in fact required, it is by no means additional. That is, knowledge of the cost function implies knowledge of the production function, and conversely[13,14]. On the other hand, a model which incorporates taxes upon factors of production does require a great deal of other information which is not needed in the consumer goods taxation model. In particular, in order to compute optimal taxes one would have to know the aggregate demand and supply functions of each of the factors of production. The reason such

information is required is that taxation (of consumer goods or their factors of production) will affect the quantities used of various factors and hence will affect the prices of the latter. When factor prices change, the consumer good production cost function will shift. Of course, the aggregate demand for a particular factor of production is the sum of firm's derived demands for that factor. Such derived demands depend upon not only the prices (including taxes) of all factors of production, but also upon the levels of consumer goods production. In short, because of substitution possibilities in production, the aggregate demand for a factor of production will generally depend upon the levels of usage of many other factors. That is, there is a great deal of "jointness" as far as factor demands are concerned. Therefore, if taxes on factors of production are included in the consumer goods taxation model, one would need to know the equilibrium response functions of all the factors of production under consideration. Also, factor taxation may affect the prices of consumer goods not contained in the consumer goods tax model and hence such consumer goods would also have to be included in the model even though such goods may have little solid waste potential.

In order to write the problem which must be solved if factor taxation is to be used, some discussion of $\pi^o - \pi(\tau) + T^o - T(\tau)$ is in order. Let $\gamma^o = (\gamma_1^o,..,\gamma_F^o)$ be the <u>exante</u> tax factor prices for each of F factors indexed by $f = 1,..,F$. Let x_{if} denote the total usage of factor f in the production of the $i^{\underline{th}}$ consumer good. The cost function for the $i^{\underline{th}}$ consumer good, C_i, is a function of factor prices as well as levels of output. Therefore, the change in profits for firms producing consumer good i, as a result of factor taxation, can be written as

$$\pi_i^o - \pi_i(\tau) = p_i^o D_i(p^o) - C_i(D_i(p^o),\gamma^o)) - p_i(\tau)D_i(p(\tau)) + C_i(D_i(p(\tau)), \gamma(\tau) + \tau) \quad , \tag{82}$$

where $\gamma(\tau) = (\gamma_1(\tau),..,\gamma_F(\tau)$ are the <u>ex post</u> tax unit factor prices

(exclusive of the tax vector τ) and $\gamma(\tau) + \tau = (\gamma_1(\tau) + \tau_1, \ldots, \gamma_F(\tau) + \tau_F)$ represents the vector of factor prices actually paid by producers (inclusive of the tax vector τ). Also, $T_i(\tau)$, the additional tax take from the producers of consumer good i, is given by

$$T_i(\tau) = \sum_{f=1}^{F} \tau_f x_{if}(\tau) \quad , \tag{83}$$

where $x_{if}(\tau)$ is the quantity of factor f used by industry i as a result of the factor tax imposition τ.

Therefore, notationally, one adds to the consumer goods tax model variables which represent factor taxes and constraints which represent the demand and supply equilibrium conditions for the factors of production under consideration. The latter are, of course, needed in order to gain estimates of $\gamma(\tau)$, the ex post tax equilibrium factor prices. This should be recognized as no easy task. In particular, the derived demand for a factor of production for a firm depends upon both output level and the entire vector of factor prices. That is, if $C(q,\gamma)$ represents the cost function for producing q units when the factor price vector is γ, it is well-known [13] that the derived demand for the $f^{\underline{th}}$ factor is given by

$$x_f(q,\gamma) = \frac{\partial C(q,\gamma)}{\partial \gamma_f} \tag{84}$$

when the firm is a price taker on factor markets. Therefore, we see that the aggregate demand for a factor of production depends upon consumer goods output levels as well as the vector of factor prices. That is, there is a great deal of jointness in such demands. In effect, the model (if all information required were known) would compute optimal levels of consumer goods production and the optimal factor mixes for each of these consumer goods levels. The constraints of the model (if all market equilibrium conditions were known) would then be used to compute the optimal consumer goods and factor taxes which would, in turn, guarantee that decentralization takes place. That is, these taxes would affect producers' and consumers' behavior in such a way so as to yield the optimal consumer goods and factor levels.

We therefore see that while notationally the consumer goods tax model can easily be expanded to include factors of production this expansion is by no means innocuous. In particular, the information requirements grow quite rapidly and may, in many cases, be preclusively expensive to satisfy .

We also see that the model can be further extended to include factors of production at levels below factors for final consumption goods. For instance, a tax upon each tree cut down could be included. However, trees are used for houses as well as for newspapers and it seems that such usages must clearly be separated as far as solid waste taxation is concerned. That is, the farther back in the production cycle one goes, the greater the need to consider general equlibrium models and hence the need to obtain great deals of information. The implication of this view is that a tax upon a tree makes a great deal of sense if one is interested in conservation, but seems to make little sense when it comes to solid waste problems.

In summary, there are several points both in favor as well as against to be made about general taxing models for solid waste control. In favor, one can say that if taxes on factors of production are utilized, then it will generally be the case that "second best" alternatives on the part of solid waste disposers may be eliminated. That is, it is entirely possible that a solid waste disposal tax will lead to increased littering or incineration. However, it is possible that encouragement at the producer level for recycling may significantly reduce the effects of "second best" alternatives at the disposal level. On the other hand, such models require a great deal of market information regarding equilibrium responses of both consumer goods and factors of production as well as solid waste responses as a function of the tax vector. Finally, there is an additional problem which to some extent makes such taxing models difficult to employ correctly. In particular, we generally must be concerned with products produced outside the region in question but whose solid waste will be felt within the region. As far as the models above are concerned, the latter

presents no problem as long as only the region in question is imposing taxes. On the other hand, if taxation is a workable tool then one may expect it to be used in several regions and therefore a particular producer may experience several different taxes from different regions. In addition, tax intervention in factor markets can lead to undesirable secondary effects if production levels of goods with relatively little solid waste potential are reduced (e.g., a paper pulp tax will tend to reduce the production of books). However, it seems quite likely that an overall solid waste agency could be constructed to in some sense coordinate the structure of taxes over the several regions. As we shall see in the solid waste taxing model below, if such charges are relatively low we may need not consider regional interactions.

SOLID WASTE POTENTIAL TAXATION

The above taxing models have the property that taxes are being imposed for the purpose of controlling solid waste decisions; however, the taxes are not upon wastes but upon goods and factors. A taxing approach which is deserving of some attention can be referred to as the taxation of "solid waste potential." Such taxes would be imposed upon wastes but not at the stage where such wastes are offered for final disposal. Instead, such taxes would be imposed upon consumer goods based upon the solid wastes inherent in the products. Such taxes, therefore, would be imposed at the consumer goods production stage, rather than at the solid waste disposal stage in order to encourage producers to provide consumer goods which are less solid waste intensive. We wish to point out that the phrase "consumer goods" above may be somewhat ambiguous. In particular, the SWA would have to identify those products which result in significant solid waste for disposal. Also, such firms as,say, large service organizations which produce large volumes of paper waste may have to be included somehow in the classification of "consumer goods." On the

other hand, it may be easier from an operational point-of-view to consider the paper factors of production of such firms as consumer goods and thereby levy taxes upon the producers of these factors based upon the solid waste potential of the products. Or, it may be more desirable to tax such firms directly for their own solid waste disposal demand and to levy solid waste potential taxes upon more easily identified consumer goods.

We now wish to point out that solid waste potential taxes are essentially no different from consumer goods and/or factor taxes.

Consider first the case where the solid waste potential of n consumer goods depends only upon the level of production of these goods. Assume there are I waste types. If industry i produces q_i units of its product, we let $W_{io}(q_i) = (W_{io1}(q_i),..,W_{ioI}(q_i))$ denote the resulting solid waste potential vector. Therefore, the total solid waste potential due to consumer goods production $q = (q_1,..,q_n)$ is given by the vector

$$W_o(q) = \sum_{i=1}^{n} W_{io}(q_i) \quad . \tag{85}$$

As noted in the previous section, a tax vector τ can be placed upon anything as long as the equilibrium response functions $p_i(\tau)$, $i = 1,..,n$, and the solid waste response $w(q)$ are known or can be easily estimated. For this case, $W(q)$ is composed of the solid waste potential vector $W_o(q)$ as well as additional wastes such as firms' own wastes,and garden trimmings, etc. For simplicity, we assume $w(q) = W_o(q)$. Knowing these response functions, let $\tau^* = (\tau_1^*,.., \tau_I^*)$ be an optimal solid waste potential tax vector found by the general model (note that such taxes may vary with consumer goods). A firm facing the tax vector τ^* will solve

$$\max_{z} \quad R(z) - C(z) - \sum_{j=1}^{I} \tau_j^* W_j(z) \quad , \tag{86}$$

where z denotes this generic firm's output level and $R(z) = D^{-1}(z)z$, and therefore its optimal output level z^* is such that

$$R'(z^*) - C'(z^*) - \sum_{j=1}^{I} \tau_j^* \frac{\partial W_j(z^*)}{\partial z} = 0 \quad . \tag{87}$$

But this merely states that if the SWA imposed a tax of

$$\tau_o^* = \sum_{j=1}^{I} \tau_j^* \frac{\partial W_j(z^*)}{\partial z} \tag{88}$$

upon the firm's level of output, exactly the same behavior will have been induced for this firm. That is, there is essentially no difference between consumer good taxation and the taxation of solid waste inherent in the consumer good.

More correctly, as noted above, solid waste associated with consumer goods generally depends more on the factor mixes used to produce these goods rather than on the level of production itself. In particular, let there be F factors of production, let $x^i = (x_1^i,..,x_F^i)$ denote the factor mix used to produce consumer good i, and let $W_{io}(x^i) = (W_{io1}(x^i),..,W_{ioI}(x^i))$ be the resulting vector of solid waste potential. Again, assume $\tau^* = (\tau_1^*,..,\tau_I^*)$ is an optimal solid waste potential vector found by the general model.

A firm facing the tax vector τ^* will solve

$$\max_{z,x} \; R(z) - \sum_{f=1}^{F} \gamma_f x_f - \sum_{j=1}^{I} \tau_j^* W_j(x) \tag{89}$$

subject to

$$\phi(x) - z \geq 0$$

where x is the firm's factor usage vector, $\gamma = (\gamma_1,..,\gamma_F)$ is the ex post factor price vector (with respect to the waste potential tax), and ϕ is the firm's production function. Therefore, the firm's optimal factor vector x^* must be such that

$$-\left(\gamma_f + \sum_{j=1}^{I} \tau_j^* \frac{\partial W_j(x^*)}{\partial x_f}\right) + R'(\phi(x^*)) \frac{\partial \phi(x^*)}{\partial x_f} = 0 \tag{90}$$

for f = 1,..,F.

On the other hand, let $\hat{\gamma} = (\hat{\gamma}_1,\ldots,\hat{\gamma}_F)$ be the ex post factor price vector when factor taxes δ_f, $f = 1,..,F$, are imposed. The firm then seeks to solve

$$\max_{z,x} \quad R(z) - \sum_{f=1}^{F} (\hat{\gamma}_f + \delta_f)x_f \tag{91}$$

subject to

$$\phi(x) - z \geq 0 \quad .$$

Therefore, the firm's optimal factor vector $\hat{x}$ must be such that

$$-(\hat{\gamma}_f + \delta_f) + R'(\phi(\hat{x}))\frac{\partial\phi(\hat{x})}{\partial x_f} = 0 \tag{92}$$

for $f = 1,..,F$. Therefore, if we set

$$\hat{\delta}_f = \gamma_f - \hat{\gamma}_f + \sum_{j=1}^{I} \tau_j^* \frac{\partial W_j(x^*)}{\partial x_f} \quad , \quad f = 1,..,F, \tag{93}$$

the factor tax vector $\hat{\delta}$ will induce the firm to behave the same as if it were faced with the solid waste potential vector τ^*. Therefore, again there is essentially no difference between solid waste potential taxation and factor taxation. The analysis above neglects some possible advantages for solid waste potential taxation over factor taxation. In particular, the concept of waste potential should take into account the recycling that takes place. Factor taxation would tend to neglect this important aspect of the problem. For example, a properly designed waste potential tax on aluminum cans could lead firms to increased efforts to encourage recycling of those cans while factor taxation, since it would apply to all cans produced regardless of recycling levels, would tend to offer no such incentive. It, however, should be noted that factor taxation can be used to encourage recycling to the extent that it reduces the cost of production with recycled materials relative to the cost of production with virgin materials.

See Section VIII for a detailed discussion of economic incentives to encourage recycling. In addition, factor taxation would, in order to avoid discriminatory appearances, have to be placed upon all firms using the same factor types. However, many of these firms may not be significant solid waste producers (in the potential sense). On the other hand, waste potential taxation could be applied to those firms or industries whose products do lead to a significant solid waste potential. Also, it seems that solid waste potential taxation would be more easily acceptable and implementable by a SWA.

SOLID WASTE TAXATION MODEL

We now turn to an alternative, and more workable, taxation model. In particular, we assume the SWA is a "benevolent monopolist" which owns and operates solid waste disposal services and wishes to maximize benefits to the users of the system. We will later argue for this model from an argument based upon the theory of general competitive equilibrium as well as for highly practical reasons.

Applying the standard analysis to solid waste, the optimal tax is found by a comparison of marginal benefits from solid waste disposal services and the corresponding marginal costs. The benefits are generally measured on a willingness-to-pay basis. Thus the amount that a household or firm is willing to pay for one additional unit of disposal services is assumed to reflect the benefit of the service to the user. In the case of households this is the standard consumer's surplus notion. For firms it equals the increment to profits associated with an added unit of disposal services. In either case a monetary evaluation of marginal benefits as a function of quantity of disposal services consumed is given by the household or firm derived demand curve for these services. The market inverse demand curve $D_W^{-1}(w)$ thus represents marginal benefits (to demanders of disposal services) as a function of total disposal services w consumed. The social cost on disposal services is assumed to be

completely represented by the costs of collection and disposal. We write this as c(w), the function developed in Section IV.

Under the above assumptions, the SWA seeks to solve its optimization problem

$$\underset{w \geq 0}{\text{maximize}} \quad \int_0^w D_W^{-1}(z)dz - c(w) \ , \tag{94}$$

where the w used here is a number which aggregates waste into a single unit of measure such as volume or weight. Formally, an optimizing w* must satisfy "price equals marginal cost" or

$$D_W^{-1}(w^*) = c'(w^*) \ . \tag{95}$$

The SWA then imposes the price (per unit) $\tau^* = D_W^{-1}(w^*)$ upon solid waste disposers in the region.

While the above has assumed that both benefits and costs associated with solid waste disposal are functions of a single waste characteristic (such as volume or weight), it is possible to generalize the analysis to allow for an assortment of waste characteristics or types when the latter considerations are important. However, the following discussion is based upon a single waste characteristic and can easily be generalized.

The use of marginal cost taxes can be justified in an entirely different fashion. Arrow[15] has shown that under appropriate assumptions competitive equilibrium is Pareto optimal and furthermore that all Pareto optimal states correspond to a competitive equilibrium for some set of parameters. By imposing taxes reflecting marginal disposal costs, the solid waste authority is in effect operating like a perfectly competitive market. By Arrow's result we know that the equilibrium prior to intervention is not Pareto optimal and that the equilibrium afterwards is. However, there is no guarantee that the latter is Pareto superior to the former. However, by an appropriate choice of endowments the post intervention equilibrium will be Pareto superior.

It is important to notice that a necessary condition for Pareto optimality to hold is that prices for all goods entering into production or consumption be set equal to marginal cost. In particular, this means that it is necessary that markets exist for all goods or that marginal cost taxes be imposed where markets fail and that no markets are characterized by monopolistic behavior. If for some reason one or more of these conditions fails and it is not possible to intervene to rectify this situation, then in general it will no longer be desirable to follow the marginal cost pricing rule in the other markets (e.g., it is no longer, in general, desirable to impose marginal cost taxes for solid waste disposal).

We now return to the willingness-to-pay approach to consider these problems in more detail. The problem with monopolistic behavior is that it leads to a restriction of output to a level below the social optimum. The imposition of a disposal tax merely serves to cut back output even more. Seethe discussion above on optimal taxation and monopolistic production on pages 50, 55-58. Another possibility is that a market will fail to exist for an alternative method of disposal. For example, suppose there is no charge for littering. Then by taxing solid waste disposal services one merely increases the rate of littering. Graphically, the situation can be represented as in Figure 4. For simplicity it has been assumed that the rate of generation of solid waste is independent of the tax and the only effect of the tax is to cause people to increase littering by the amout that the demand for disposal services is reduced. Thus the inverse demand curve, D_L^{-1}, for littering rights is a function of both ℓ and τ. As has been done before for disposal services, we can derive a net marginal benefit curve for littering dependent on both ℓ and τ. The effect of imposing the tax τ^* is to increase benefits by an amount equal to area A by reducing the demand for disposal services while benefits are reduced by an amount equal to area B as a result of the increased litter. Depending on the specific demand and cost functions, the

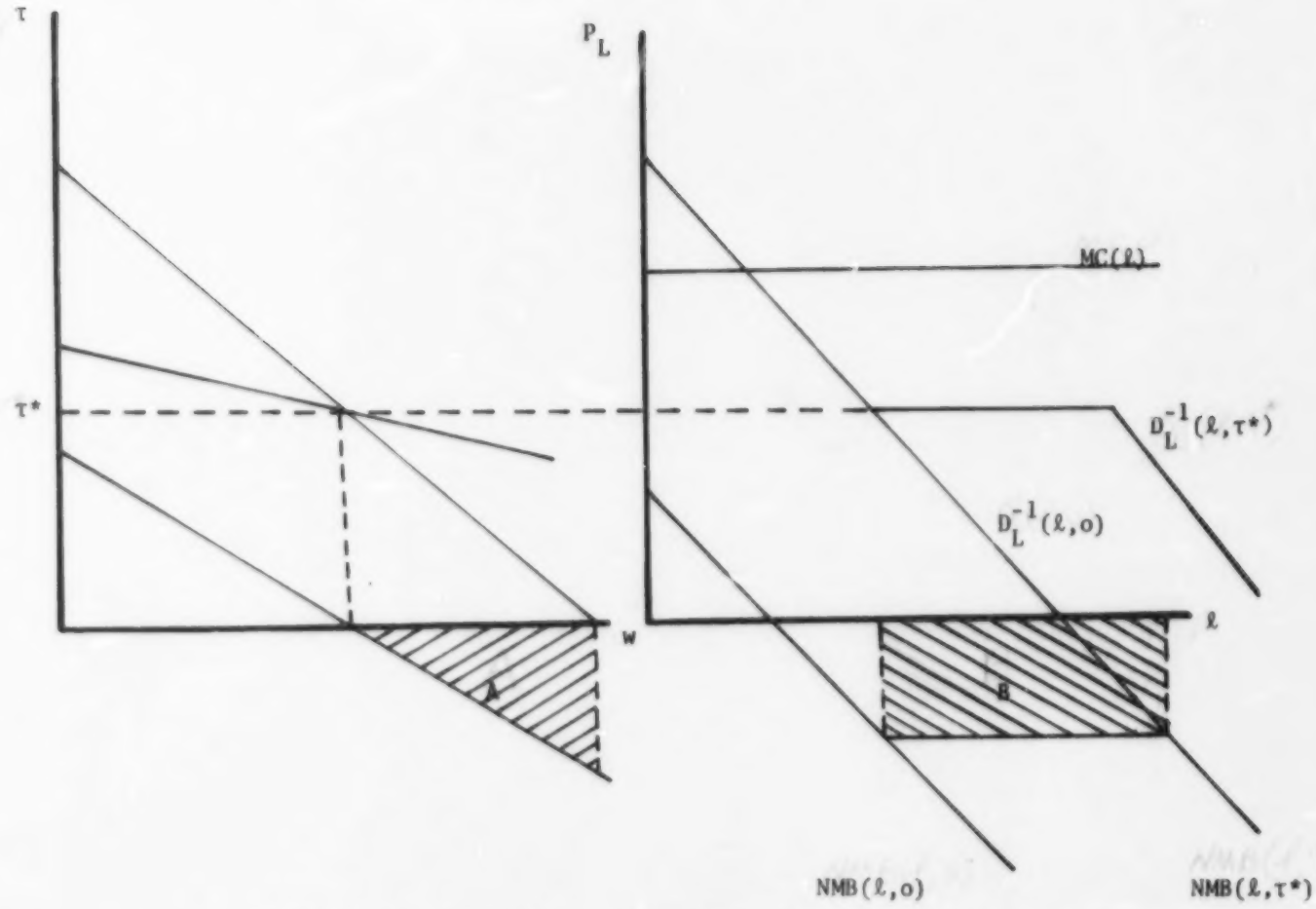

Figure 4. Comparison of benefit gains due to reduced demand for disposal services and benefit losses due to increased littering

net result may be increased benefits (e.g., area A > area B), but it is easy to see that the optimal tax would have been somewhat less than τ^* since the marginal increment to area B is greater than the marginal increment to area A for all τ in some neighborhood of τ^*.

These difficulties are merely special cases of the general theory of the second best. The theory in this area states that, except in special situations, when maximizing a function if it is impossible to meet some of the conditions for a maximum, then it is no longer desirable, in general, to satisfy the other conditions. In the case of a government composed of a number of semi-autonomous agencies this should not necessarily suggest that a solid waste authority should refrain from marginal cost taxing because it doesn't simultaneously have the power to impose air pollution taxes. In such a decentralized government it would not be expected that each agency could control all the spill overs from its policy. Rather the relevant criterion is whether there exist or could exist agencies capable of effective control in spill over areas. Thus in the situation suggested above if there exists an air pollution control board that has the ability to optimally regulate generation of air pollutants, the solid waste authority is justified in using marginal cost taxing allowing the APCB to adjust optimally the generation of air pollutants (possibly by marginal cost taxes in that area).

It is also worth considering the possibility that optimality may require the imposition of a tax greater than τ^*. This would occur if for example the imposition of a tax resulted in substitution into factor or consumer goods which involve an external economy (e.g., a benefit not reflected through a market machanism). For example, if such a tax resulted in a reduced demand for glass bottles and consequently led to a reduction in broken glass on streets and playgrounds, there would be a benefit to society over and above the savings in disposal costs, which would be equal to the societal benefit from the reduced amount of broken glass. Optimality would then require the setting of a tax higher than τ^* to capture the full benefits. Again, these effects should only be considered if there is

no agency which has the power to control the relevant external economy. From a practical point of view one would anticipate that the external diseconomies would dominate the analysis for solid waste disposal services. Thus it would be expected that optimal taxes for disposal services would be bounded above by the marginal cost taxes.

Despite these "second best" imperfections in the marginal cost approach , the latter offers the advantage that it is operational on a practical level primarily because the informational requirements are manageable. Specifically, all that is needed is a knowledge of the marginal cost curve for disposal services and perhaps the elasticity of demand for disposal services at the initial level of demand. Contrast this with the difficulties in optimization with the more general summed consumer's surplus measure that was discussed earlier. What is more, the second best problems, while being an important consideration, may be insignificant in many cases or may be neutralized by suitable collateral policies. Our study has indicated that the major secondary market imperfections that are of significance in solid waste control consist of first monopolistic production and secondly socially undesirable alternatives to disposal services such as incineration, water pollution, and littering.

Monopolistic production may be of limited significance for a number of reasons. First, it is questionable to what extent monopolies exist. It should be noted that economists have a great deal of difficulty identifying monopolies. The problem is that the usual identifying characteristics of monopoly (single seller, downward sloping demand curves, or above average rates of return) can (and frequently are) consistent with competitive behavior. Thus many enterprises that are thought of as excercising monopolistic power may, on closer examination, be found to act competitively. Secondly, even if in a particular municipality monopoly elements exist then unless they represent a significant contribution to the rate of solid waste generation, they can probably be ignored since the gains from taxes will far overshadow the losses from taxing waste from monopolistic production. While even in this case it is true that

optimality would require taxes somewhat less than marginal cost, the cost of the informational requirements for making the appropriate adjustment would probably exceed the gains. Finally, even if monopoly elements are significant, an argument can be made, as noted earlier, that these effects should be ignored since there already exist government agencies responsible for controlling monopolies (e.g., the Justice Department).

As for the possibility of socially undesirable substitutions, the probability of increased water pollution is minimal since generally few firms (in urban areas where solid waste is a serious problem) have access to water bodies and in those cases where it is significant there should exist regulatory agencies responsible for water quality. Many municipalities have outlawed incineration, thus eliminating the possibility of that type of substitution legally. In most areas where incineration is legal, one would expect that air quality is not a significant problem, and thus the marginal social costs of incineration are near zero, so that such substitution is in fact desirable. In cases where incineration is a serious problem, the use of solid waste taxes would have to be combined with control over incineration (perhaps outlawing it). Littering provides a more complex problem. It is not clear that substitution in this case will be of such a magnitude as to merit consideration, but if it is significant there exists the problem that there seem to be no really effective control mechanisms available. Even here,however, the substitution effects of a tax can be neutralized by simultaneously offering free solid waste disposal at convenient locations. Thus persons who would have an incentive to substitute into littering would instead take wastes to such centers.

On the basis of the discussion above, it would appear that in many, if not most cases, marginal cost taxing is not only operational from a practical point of view, but can also be made free from detrimental secondary effects. For these reasons, despite a weaker theoretical foundation than for the more general models, such an approach

represents a strong and practical tool for solid waste management. We now turn to a consideration of the mechanics of setting tax levels.

As was noted earlier, the optimal tax τ^* in a steady state model satisfies the relation $\tau^* = D_W^{-1}(w^*) = c'(w^*)$. The simplest approach to finding an optimal tax would be to set a tax in each period (a period being defined as the length of time necessary for the level of demand to adjust to some neighborhood of the new equilibrium) equal to the marginal cost of disposal of wastes at the rate of generation at the end of the previous period. In the case of downward sloping demand and upward sloping marginal cost curves, this results in a standard cobweb adjustment path. Depending on the slopes of the two curves, the result of this iterative process can be either convergence or divergence. Beyond the problem of convergence (which probably isn't significant) there is the practical problem that the sequence of tax levels that would result may be politically unpalatable since it would appear capricious to say the least. This is illustrated in Figure 5 where the adjustment cobweb is shown for this simple taxing rule. The sequence of taxes describes a dampened oscillation about the fixed point. It is the fact that taxes will be alternatingly increasing and decreasing that will appear capricious.

It should,however, be possible to do better with even a rough estimate of the slope of the demand curve for disposal services at the initial equilibrium. Then, by assuming a linear demand, an approximation to the optimal tax can be calculated. Taking that value as a starting point, the fluctuations in the level of the tax during the iteration process should be considerably reduced. The adjustment path using this technique for the same demand and marginal cost curves as in Figure 5 is shown in Figure 6 . While the tax levels again oscillate the range of the fluctuations is considerably less than in Figure 5 . It is worth pointing out that the more flat the marginal cost curve or the more vertical the demand curve, the more correct it would be to set the tax equal to the marginal cost at the pre-tax level of demand for disposal services. Indeed,in the limit where the marginal cost curve equals a constant, the optimum is to set the tax equal to

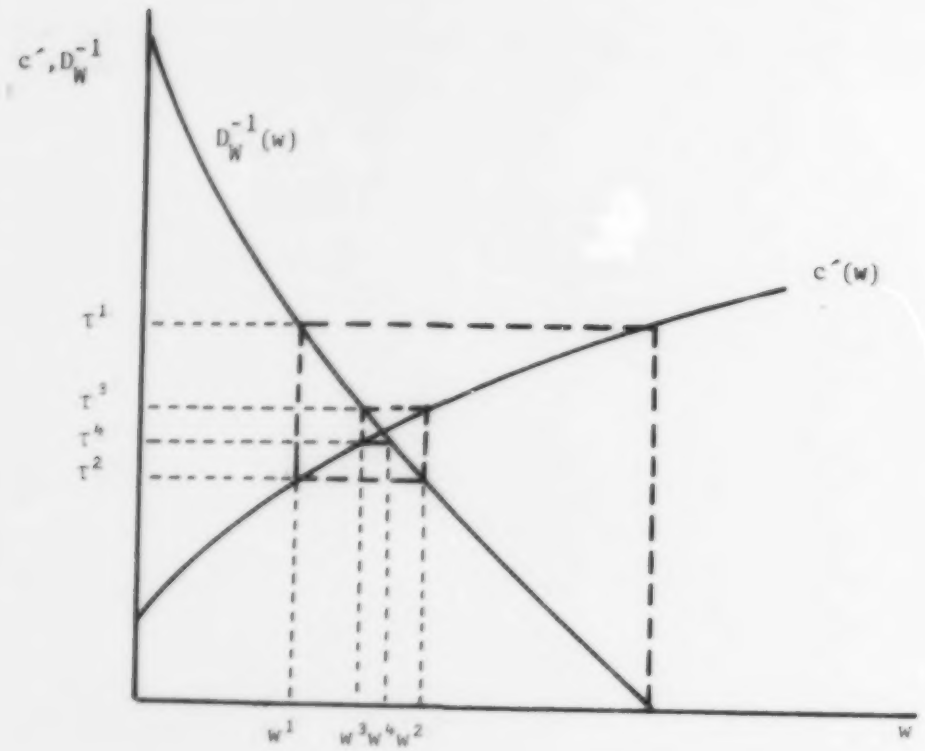

Figure 5 . Tax adjustment path due to iterative taxing scheme

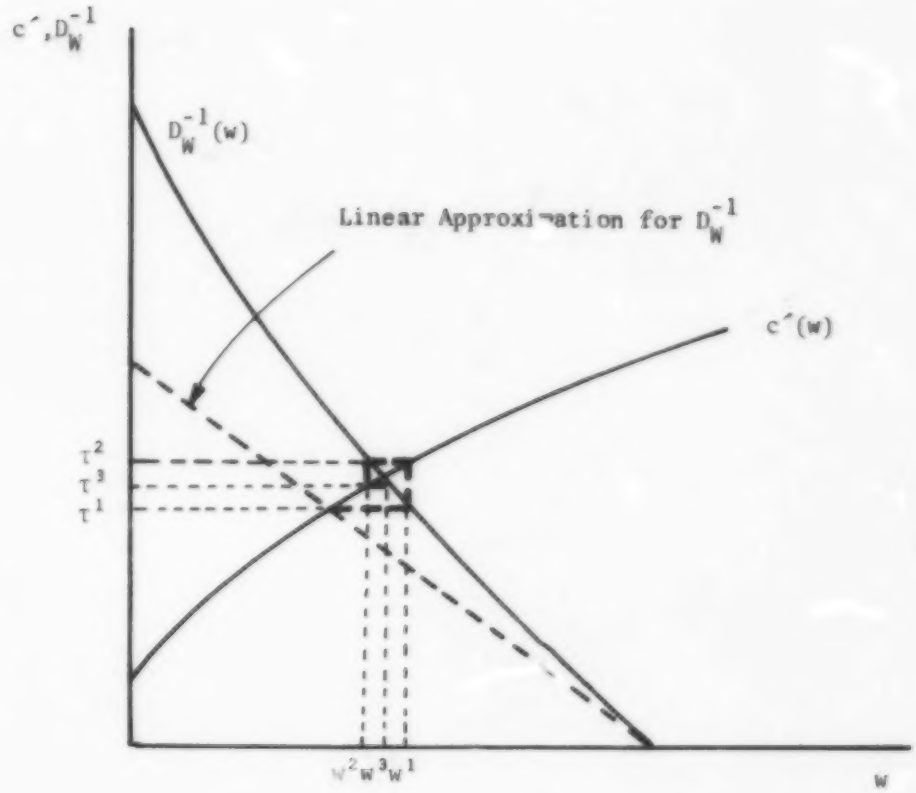

Figure 6 . Tax adjustment path due to iterative taxing scheme when demand is linearized

the constant marginal cost regardless of what level of demand eventually develops.

In reality, one would expect the situation to be even easier to handle than the above discussion would indicate. This is because the marginal cost curve for disposal services is probably downward sloping. Looking at Figure 7 it is evident that the simple iteration scheme results in a continually increasing tax level. As a result the behavior of the tax over time no longer looks capricious. Indeed, an argument could be made for a gradually increasing tax even if the solid waste authority knew the optimal level initially. The reasoning being that it gives firms and individuals time to adjust.

There is one danger in the use of tax iterations that should be pointed out. Such schemes invariably introduce uncertainty into the decision making process of businesses and individuals. In particular, firms may have an incentive to defer investment in equipment that would reduce solid waste flow until the tax reaches a stationary equilibrium. It is at this point that they can determine the optimal level of investment. Thus the use of an iteration may cause firms to defer investment in solid waste reduction related capital while the use of a single unchanging tax would eliminate this incentive to defer investment.

It is worhwhile to briefly consider how significant the gains from a tax might be. If we take the area between the marginal cost curve and the deamnd curve as an appropriate measure of these benefits, it is clear that the shape of the demand curve will be critical; the steeper the demand curve is for $\tau < \tau^*$, the equilibrium tax, the less the benefits. If we consider the case where the marginal cost curve is a constant, k, and the demand curve is linear with slope α the benefits are given by $\frac{k^2}{2\alpha}$. This just says that if the demand for disposal services is comparatively insensitive to the level of the tax, then benefits will be comparatively small. An important question then is what is the average slope of the demand curve for $\tau\varepsilon[0,\tau^*]$. Unfortunately there is little data available on the responsiveness of

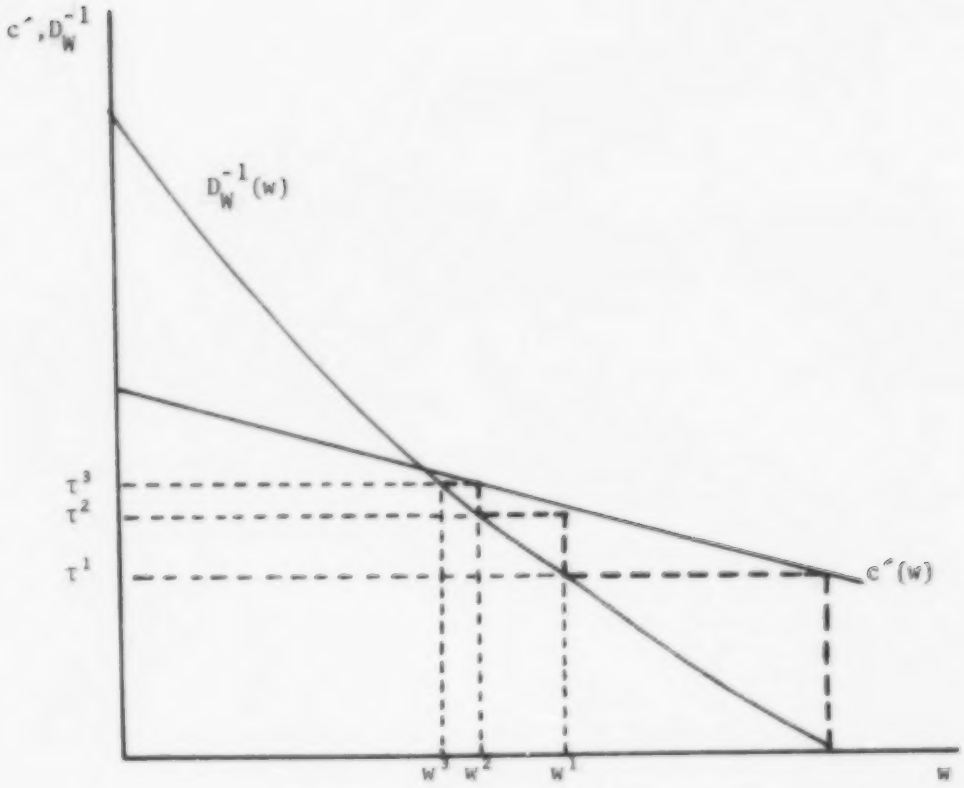

Figure 7 . Tax Adjustment path under decreasing marginal cost

demand for disposal services to the level of the tax (see McFarland, et al.[16] for an estimate of the demand elasticity for disposal services). One likely shape is shown in Figure 8; at low and high levels of τ the demand curve is steep while in between there is a range where the demand curve is comparatively flat. The theoretical justification for this particular shape is that low values of τ may be insufficient to encourage the investment in information necessary to adjust optimally. At the intermediate valuesthis barrier is overcome and thus adjustments that would have occurred for low values of τ, except for these informational costs, are not observed until this intermediate range. Finally, at high levels there is little adjustment possibly since most of the feasible substitutions have already occurred. Figure 9 illustrates the explanation. The information cost is assumed constant at I. By adding the fixed information cost to the usual shaped demand curve and rounding the corner (shown in dotted line) one gets the hypothesized shape used in Figure 8.

Returning now to Figure 8 it becomes apparent that the net benefits from a tax, as represented by the area between the marginal cost curve and the demand curve, will be highly sensitive to the location of the marginal cost curve. In particular, the critical question is where the marginal cost curve falls relative to the responsive portion of the demand curve. As can be seen in the figure, the net benefit associated with the imposition of the marginal cost tax, when the marginal cost curve is given by $c_1'(w)$, is the cross hatched area while for $c_2'(w)$ the benefit is the whole of the shaded area. If, in fact, the marginal cost curve intersects the demand curve in the unresponsive segment, there is a serious question as to whether the benefits from the tax will be sufficient to offset the cost of policy implementation and operation. This is of course an empirical question and one deserving of an answer. However, even if the gains from the impositions of a tax are insufficient to justify intervention, it may be possible through the use of a collateral policy to shift the disposal service demand curve so as to increase responsiveness in the relevant range, thus making taxation a useful tool. We present such a possibility in Section VIII.

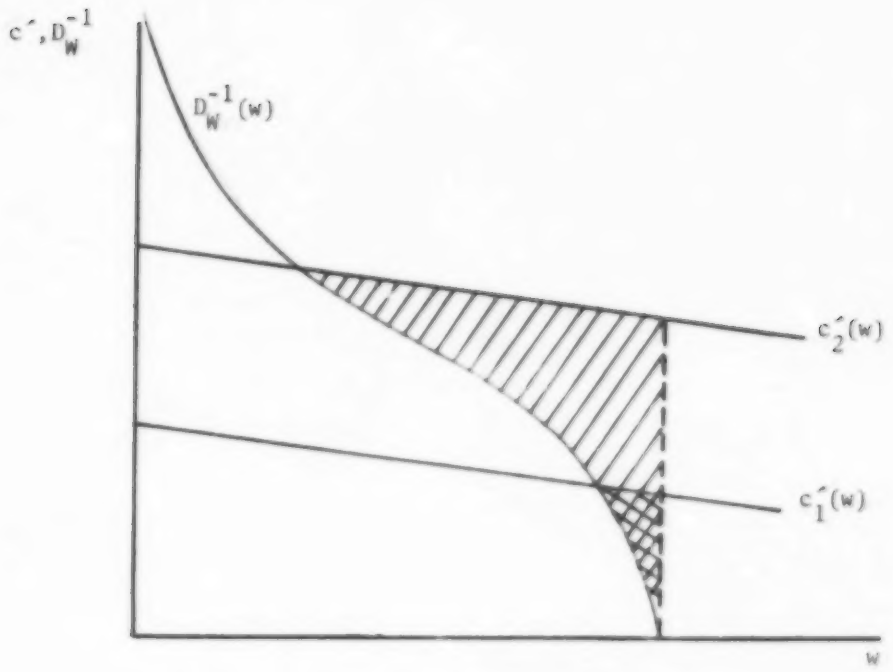

Figure 8 . Sensitivity of benefits to optimal taxes with respect to a shift in marginal cost

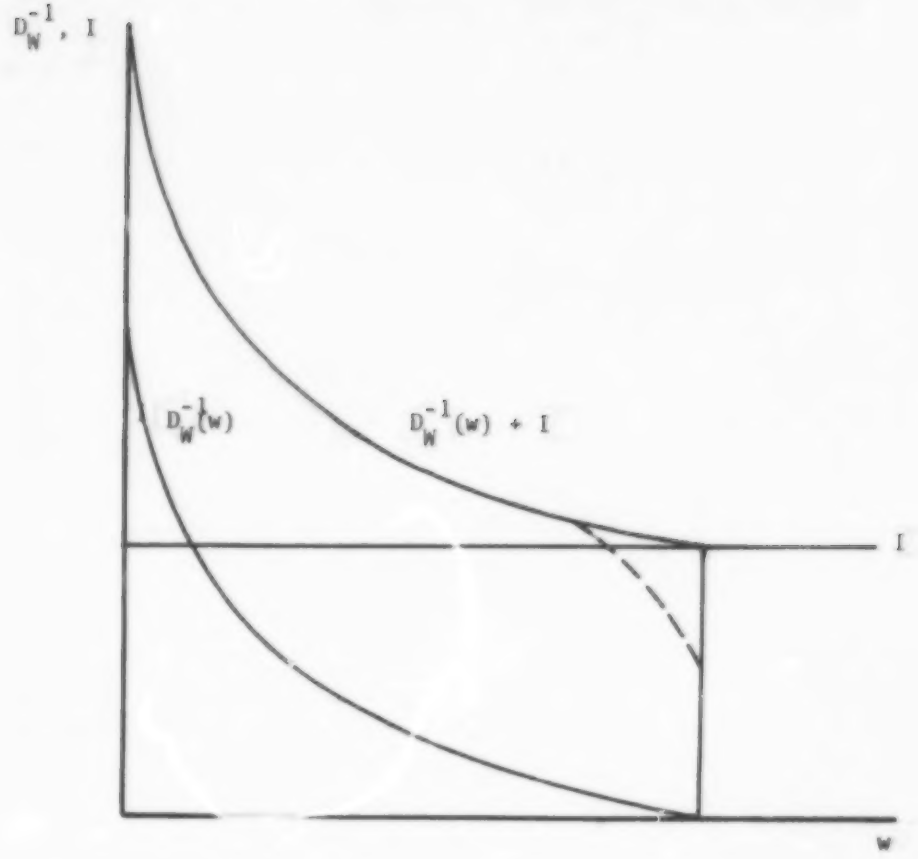

Figure 9. Sketch of justification for demand curve shape of previous figure

SECTION VII

ECONOMIC EFFICIENCY AND PROPERTY RIGHTS IN SOLID WASTE POLICY MANAGEMENT

In recent years economists have become increasingly interested in the relationships between the definition of property rights and economic efficiency. It has been shown that when these rights are well defined and transaction costs are sufficiently small, then the final allocation of property rights is the same, regardless of the initial allocation. This perhaps surprising result is found in Coase.[17] The reasoning is that resources will always be put to their most valuable use regardless of the initial pattern of ownership, since it will always be worthwhile to bid these resources away from less valuable uses. This result suggests that under certain circumstances the specification of private property rights, where previously rights were undefined or were communal in nature, will facilitate the exchange of these rights and result in increased economic efficiency.

It has been suggested that such an approach may have considerable value for environmental quality control. In particular, the reader is referred to Dales[3] for elements of such a view in the context of water pollution. The private property rights approach is based on the fact that in many instances the environment is held in communal ownership and is consequently overutilized. In particular, this is true for the assimilative capacity of the environment for solid waste and municipal disposal services. To the extent that individuals and firms have the right to unlimited use of these resources at zero cost, these resources will be overutilized. This problem is essentially analogous to the difficulties of common hunting grounds and fisheries discussed by Demsetz[18].

If, however, transferable private property rights for solid waste disposal services are defined (presumably in terms of weight or volume), a solid waste authority can restrict the utilization of

solid waste disposal services. This can be accomplished by issuing a fixed number of such rights (measured, say, by weight per unit time). It is important that an efficient market for these rights develop so that the disposal rights will be put to the most valuable use. This leads to the possibility that given a policy (say, a quantity limit per unit time the solid waste authority will accept for disposal), a private market will define optimal prices, thereby eliminating a good deal of the usual informational requirements.

As Dales[3] points out in his discussion of water pollution, such markets (as well as taxing mechanisms), by producing positive prices for assimilative stream capacity, will encourage firms to some level of self-treatment or production process modifications. In the case of solid waste, the latter may, in some cases, be feasible (e.g., substitution of returnable bottles for non-returnable bottles). However, the solid waste analogue of self-treatment is recycling. That is, one method available to firms to reduce solid waste output for <u>disposal</u> is to use some level of recycled materials. Of course, recycling for the purpose of reducing the demand for solid waste disposal services has at least one serious drawback. To a large extent, the materials which are recyclable or usable for by-products <u>and</u> which are easily obtained by the producer (e.g., a direct result of the production process itself) are already largely used for such purposes. However, the recyclable material which leaves the control of the producer (e.g., a newspaper or an aluminum can) forms, by far, the largest portion of the salvage potential in municipal solid wastes. Therefore, the above mentioned analogy between self-treatment by firms (in the case of water pollution problems) and firms using recycled materials to reduce solid waste disposal needs is not as tight as one might first think. However, if markets can be created for recyclable materials, then the analogy becomes quite meaningful.

In Section VIII we will discuss the problem of intervention to encourage the development of markets for recyclable materials.

THE BENEFITS EFFECT OF A PRIVATE MARKET FOR SOLID WASTE DISPOSAL SERVICES

In the above discussion there is a distinction between "efficient use of solid waste disposal services" and "optimal use" as defined by the benefits measure developed in Section V. To bring out the relationship between the two, we now develop the implications a private regional market for solid waste disposal rights has for benefits maximization. In particular, we wish to answer the following question:

> If a private market for solid waste disposal rights is created and an equilibrium price (say, dollars per unit weight) is arrived at for such disposal services, then what measure (if any) of benefits is being maximized by the creation of such a market and equilibrium price?

To answer this question, we proceed as follows. Assume there are n firms indexed $i = 1,..,n$. Let x^i be the decision vector for the $i^{\underline{th}}$ firm and let $f_i(x^i)$ be the profit accrued to the $i^{\underline{th}}$ firm when it decides upon the input vector x^i. Let $W_i(x^i)$ be the solid waste produced for disposal by the $i^{\underline{th}}$ firm when the $i^{\underline{th}}$ firm is using the input vector x^i. Let w be the regional limit (per unit time) upon the quantity of solid waste that the authority will accept for disposal services.

If there is a price λ per unit of solid waste, then the $i^{\underline{th}}$ firm will seek to solve its own profit maximization problem. That is, the firm seeks to compute its modified optimal profits.

$$\mathscr{P}_i(\lambda) = \text{maximize } f_i(x^i) - \lambda W_i(x^i)$$
$$\text{subject to } x^i \in X^i , \tag{96}$$

where x^i is the set of feasible decisions available to the $i^{\underline{th}}$ firm. Let $x^i(\lambda)$ be an optimizing vector for the above optimization problem of the $i^{\underline{th}}$ firm and let

$$w_i(\lambda) = W_i(x^i(\lambda)) \tag{97}$$

denote the resulting level of solid waste offered for disposal. Then,

$$w(\lambda) = \sum_{i=1}^{n} w_i(\lambda) \tag{98}$$

denotes the total quantity demanded for solid waste disposal services when λ is the per unit price for such services. It is well known that the function $\mathscr{L}_i(\lambda)$ is concave in λ (e.g., Luenberger[19]). Also, by non-negativity of the function $W_i(x^i)$, it can easily be shown that $\mathscr{L}_i(\lambda) \geq \mathscr{L}_i(\gamma)$ and $w_i(\lambda) \geq w_i(\gamma)$ if $\lambda \leq \gamma$. This implies that $w(\lambda)$ is a non-increasing function of the solid waste disposal price λ.

Now assume $\lambda^* \geq 0$ is an equilibrium price. That is, λ^* is such that

$$w(\lambda^*) = w \tag{99}$$

or, equivalently, λ^* is the price which equates the fixed supply w with demand $w(\lambda)$. Now, when the $i^{\underline{th}}$ decision unit is faced with solid waste disposal price λ^*, it will solve its own optimization problem (96) and decide upon vector $x^i(\lambda^*)$. Therefore, for each $i = 1,..,n$, the following condition holds:

$$\begin{aligned} &x^i(\lambda^*) \text{ solves} \\ &\qquad \max\ f_i(x^i) - \lambda^* W_i(x^i) \\ &\qquad \text{subject to } x^i \in X^i \end{aligned} \tag{100}$$

Also, by assumption, the following two conditions hold:

$$w = w(\lambda^*) = \sum_{i=1}^{n} W_i(x^i(\lambda^*)) \quad , \tag{101}$$

and

$$0 = \lambda^* \left[\sum_{i=1}^{n} W_i(x^i(\lambda^*)) - w \right] \quad . \tag{102}$$

Now, the crucial point is that conditions (100-102) are necessary and sufficient for $(x^*, \lambda^*) = (x'(\lambda^*),\ldots,x^n(\lambda^*),\lambda^*)$ to be a saddle point for the following optimization problem:

$$\max \sum_{i=1}^{n} f_i(x^i)$$

$$\text{subject to} \quad \sum_{i=1}^{n} W_i(x^i) \leq w \qquad (103)$$

$$x^i \in X^i , \quad i = 1,..,n .$$

It is well known that if (x^*, λ^*) is a saddle point, then x^* is optimal[19] so that we have the following answer to the above postulated question.

> If a solid waste disposal authority sets a quantity limit w and if an efficient private market acts to equilibrate supply and demand for the limited disposal services, then the resulting actions of the n decision makers are such that the sum of the individual objective functions of the n decision makers is maximized subject to the authority's quantity constraint. That is, the resulting vector of decisions x^* solves the optimization problem (103).

The generality and implications of the above result are clear. For instance, the result in no way depends upon solid waste notions. Also, the information requirements are relatively smaller than for a controlled system (we will have more to say about information requirements and/or costs later in this section). For instance, one need not know the profit functions of the n firms, although

of course, the authority would have to keep track of each firm's disposal quantities.

The attractiveness of using property rights to generate a market for environmental services is somewhat mitigated in certain situations. For instance, if there are several firms discharging wastes to a waterway and a market is created for which these firms are to purchase limited quantities of the stream's assimilative capacity, our result implies that the sum of the firms' individual objectives will be maximized. However, if some of the firms have considerable monopoly or oligopoly power in their respective product markets, the result will then be that the product output levels of each of the firms will diverge from the optimal levels which would occur if we were to use the benefit measure developed in Section V. Broadly speaking, there seems to be no justification for maximizing the sum of the polluting firms' profits subject to a stream assimilative capacity constraint (see the discussion of monopolies on pages 52, 55-58). This methodological problem of welfare economics seems to have gone unnoticed by Dales[3].

Therefore if a solid waste authority sets a quantity limit and then establishes a market for equilibrating the demand and fixed supply of disposal services, the resulting decisions of the n decision makers will be "efficient" in the sense that optimization problem (103) will have been solved. On the other hand, it is generally <u>not</u> the case that such decisions will be "optimal" in the welfare sense of Section V.

To illustrate the latter important point, we now present a modified version of the welfare benefits maximization problem of Section VI and compare it with the results which would obtain if a private market for solid waste disposal services were created.

Let q_i, $i = 1,..,n$, denote the output level of firm i. Let

$D_i^{-1}(q_i)$ be the inverse demand function for the output of firm i and let S_i^{-1} be the $i^{\underline{th}}$ firm's marginal cost function. For simplicity, we assume that the demand functions D_i^{-1} are independent. That is, the unit price of good i does not depend upon q_j. Assume also that the solid waste authority has set a total quantity limit upon the supply of waste disposal services that it will offer.

Under these assumptions, the benefits measure of Section V implies that the following optimization problem is to be solved.

$$\max_{q} \sum_{i=1}^{n} \int_{o}^{q_i} (D_i^{-1}(z_i) - S_i^{-1}(z_i))dz_i$$

$$\text{subject to } \sum_{i=1}^{n} W_i(q_i) \leq w \tag{104}$$

Suppose we let (q^*, γ^*) be a saddle-point for the optimization problem(104). Then it is <u>not</u> true that if a price of γ^* is imposed for each unit of solid waste disposal services the firms will respond by producing q_i^* and disposal waste $W_i(q_i^*)$. The reason firms will not so respond is that if, for instance, they are profit maximizers, each firm, when faced with γ^*, will maximize its modified profit function

$$D_i^{-1}(q_i)q_i - C_i(q_i) - \gamma^* W_i(q_i) \quad , \tag{105}$$

where $C_i(q_i)$ is the $i^{\underline{th}}$ firm's production cost function, and the sum of the n profit terms

$$D_i^{-1}(q_i) - C_i(q_i) \quad , \quad i = 1,..,n, \tag{106}$$

is <u>not</u> the objective function of(103). In particular, we have at hand a special case of the <u>mixed-economy problem</u> which, in turn, leads to severe difficulties as far as price decentralization is concerned.

Also, recall that our basic result implies that if an equilibrium price λ^* is obtained $(w(\lambda^*) = w)$, then the following optimization

problem, assuming profit maximization, will have been solved:

$$\max \sum_{i=1}^{n} \left(D_i^{-1}(q_i)\, q_i - C_i(q_i)\right)$$

$$\text{subject to} \quad \sum_{i=1}^{n} W_i(q_i) \leq w \quad . \tag{107}$$

It is clear that problems (104) and (107) are not equivalent problems. However, at the expense of a greater informational requirement and more solid waste authority intervention, a market can be constructed so that an equilibrium price λ^* will lead to firm decisions which optimize (104). This can formally be accomplished as follows. The solid waste authority announces that it will provide each firm with the consumers' surplus associated with the firm's product output. That is if $\bar{q}_i$ is decided upon by the $i^{\underline{th}}$ firm, the solid waste authority will provide the firm with

$$\int_0^{\bar{q}_i} D_i^{-1}(z_i)\,dz_i - D_i^{-1}(\bar{q}_i)\bar{q}_i \quad . \tag{108}$$

Under this condition, the $i^{\underline{th}}$ firm's new profit function is (by adding the above term to the old profit function)

$$\int_0^{q_i} D_i^{-1}(z_i) - C_i(q_i) \quad , \tag{109}$$

which is, of course, the $i^{\underline{th}}$ term of the objective function of (104). Therefore, by our basic result, a market mechanism to equilibrate supply and demand for solid waste disposal services can be formed which will lead to a social optimal solution (in the sense of optimization problem (104)) if the solid waste authority provides firms

with the consumer surpluses associated with their respective outputs.

We wish to point out that if each of the firms is a price taker in its product market, then optimzation problems (104,107) are essentially the same and therefore a market mechanism for equilibrating supply and demand for solid waste disposal services will lead to a social optimal. Since the argument which establishes this result would require some fixed-point notions, we merely sketch the idea of the argument. Since each firm is a price taker, it cannot affect the selling price of its product. Therefore, D_i^{-1} is a constant for each $i = 1,..,n$.

On the other hand, as market prices are developed for solid waste disposal service, the above output price constants will change since each of the marginal cost functions of the n firms is changing and therefore the supply function is shifting. However, it can be shown that the equilibrium price λ^* (which equilibrates supply and demand for disposal services) is such that firms will respond so that the following optimization problem is solved:

$$\max_{q} \sum_{i=1}^{n} \int_{0}^{q_i} [P_i^* - S_i^{-1}(z_i)]dz_i \tag{110}$$

$$\text{subject to} \quad \sum_{i=1}^{n} W_i(q_i) \leq w \quad ,$$

where P_i^* is the equilibrium ouput price for the product of the $i^{\underline{th}}$ firm. It is clear that (110) is the same as (107)and is also the same as (104)when the constants D_i^{-1}, $i = 1,..,n$, are the ex post product output prices.

PROBLEMS ASSOCIATED WITH A PROPERTY RIGHTS SYSTEM

While the theoretical arguments indicate that the use of property rights to control solid waste may have important advantages, it is worthwhile to consider difficulties that would face such a system in

practice. From a practical level, the most obvious problem is how to regulate the system so that all disposal rights are honored and services are not rendered in excess of rights owned. On the other hand, it is important that the cost of these monitoring activities be small relative to the savings in disposal costs, for it is the savings net of enforcement costs that must be compared with societal benefits.

The enforcement problems at the point of collection are actually two fold. First, it must be possible for the collectors to know how much each firm is allowed to dispose of that day. Secondly, it must be possible to measure what each firm disposes of. Obviously it is important that disposal rights be defined in terms of some readily observable quantity, probably volume or weight. It should be noted, however, that this will be sub optimal (neglecting enforcement costs) if the relevant characteristics determining the social cost of solid waste is something more complex (e.g., some function of biodegradability or toxicity).

Probably the easiest way to keep account of the disposal rights available to each firm is through a ration ticket scheme. Presentation of a ticket would be evidence of the right to the disposal services detailed on the ticket. To avoid the costs of requiring the presence of an agent for each firm at the time of collection, ration tickets could take the form of stickers and pasted to the waste container. Another possible approach that has been used as a monitoring device in some areas is the issuance of waste containers (plastic bags or cardboard boxes) that carry with them the right to disposal of a volume equal to that of the container, i.e., only waste in these containers is collected. The specific methods of dealing with these problems will vary from municipality to municipality, but they must be solved if such a system is to work, for property rights only exist to the extent that they are enforceable

As we noted earlier, the results of this section depend on the assumption that transaction costs are small relative to the market price of the disposal rights. Obviously as the transaction costs increase, exchange will decrease and the potential gain from trade will be largely unrealized. It is not known to what extent in an actual application transaction costs would impede trade, but such costs could be important enough so that a policy based on property rights would have to be considered in conjunction with efforts by the solid waste authority to lessen the initial cost of identifying exchange partners.

So far, the discussion has only focused on the more obvious mechanical problems of the efficient operation of such a system. There is, however, the major theoretical difficulty discussed above. That is, when monopoly or, more generally, noncompetitive influences are present, it is no longer true that a solid waste market mechanism will lead to an optimal solution (in the sense of Section V). However, as we have pointed out above, under certain conditions the solid waste authority could intervene in the market itself to bring about a social optimal. Also, as we have pointed out, this would greatly increase the informational requirements for the solid waste authority, and these additional requirements are precisely those which a property rights system was originally supposed to overcome.

A final problem confronting the solid waste authority in the use of property rights is the determination of the optimal quantity of rights (w) to be allocated. It appears that there is no simple solution to this problem. Indeed, the optimal quantity will probably fluctuate seasonally or even from week to week. Without an obvious point that corresponds to optimality, the solid waste authority must rely on subjective guesses or else incur the cost of the informational requirements that this approach was originally designed to avoid.

While the discussion in this section has been largely in terms of the industrial sector, the same system could be applied to the consumption sector. It would appear, though, that the problems associated with

the use of property rights to achieve a waste constraint are merely exacerbated in this case. It could be argued that transaction costs are smaller than in industry, but by the same token so is the average value of possible transactions. It should be remembered that the crucial relationship is the relative (not absolute) magnitude of transaction costs and average value of rights exchanged. Probably the greatest difficulty would be an increased possibility of second best problems as consumers substitute incineration and littering for the now scarce disposal rights.

Thus, despite the first glance attractiveness of intervention through property rights, this approach suffers from weaknesses that may render it inappropriate for solid waste control in most situations.

SECTION VIII

ECONOMIC INCENTIVES FOR RECYCLING

As long as there is production and consumption, there will be residuals generated. Intervention through a waste disposal tax can reduce the volume of wastes by encouraging substitutions into less solid waste intensive products and techniques of production. Another alternative is to take the residuals that are generated as given and intervene to encourage recycling of at least a portion of the wastes. Indeed, over one half of municipal wastes has salvage value. The recycling of solid waste then can serve not only to reduce the burden on municipal waste disposal, but also mitigate to some extent increasingly effective resource constraints. The question then is how to encourage the increased exploitation of this salvage potential.

Currently the only type of salvage from municipal wastes that is being conducted to any appreciable extent is the recovery of steel cans after incineration [4] The main impediment to increased resource recovery, after solid waste has been collected, is high separation costs. Labor costs make manual separation impractical, and mechanical techniques generally can not adequately control contaminents and thus the result is a comparatively low grade and unsalable product. New techniques in resource recovery and improvement in existing techniques are continually being developed. However, much work needs to be done before salvage from municipal wastes will be practical on a large scale.

Thus the main difficulty for increased recycling lies in the sorting costs. Indeed, it appears that efficient collection and disposal practices run counter to reclamation. In particular, the introduction of compactor trucks and milling procedures precludes subsequent separation. Thus, with current technology, the collection of many recyclable items must occure before mixing with other wastes in order for recycling to be feasible on a large scale. The latter is almost self-evident for, say, newspapers and aluminum cans but not so for, say,

ferrous metals. On the other hand, if solid wastes are to be burned for the purpose of saving fuel in the production of electricity (a different type of "recycling") then, of course, separation before mixing with other wastes is somewhat meaningless. This report assumes that "recycling" does not include such possibilities as burning wastes for the conservation of other fuels. Rather, such savings are incorporated into the cost function c(w) for disposing of the waste vector w (see Section IV). It is also interesting to observe that recycled resources are in direct competition with the corresponding virgin resources. Furthermore, since currently recycled resources constitute relatively small portions of the respective markets for these resources (virgin plus recycled), the market demand prices for the recycled portions are, for all practical purposes, determined by the market conditions for the corresponding virgin materials. Therefore, many of the current recycling operations are marginal; small fluctuations in price can wipe out potential profits. In addition, this means that in order to be economical for salvage and processing, the waste materials must be of high grade. As a consequence, the salvage industry is centered around wastes from production for it is at this level that wastes are produced in sufficient volume and of sufficient purity to be economical. Many firms have an additional incentive for recycling some of their own wastes since many municipalities handle such wastes at a charge by private disposal services. Figures show that a quarter of major manufactured materials are salvaged[4]. Undoubtedly, the potential is there for an even greater rate of salvage.

Recovery from consumer wastes is conducted primarily through small junk dealers, civic organizations, and recycling centers. The willingness of consumers to segregate recyclable materials from wastes has increased with the growing awareness of and concern for the environment, but still the quantities involved are insignificant from the point of view of solid waste management. The difficulties in recycling household wastes include the lack of an assured quantity and quality of material, the high costs of collection, and the

reluctance of households to engage in sorting activities. We will later consider policies that may overcome these obstacles

Darnay and Franklin [4], in a detailed study of the salvage industry, concluded that for the most part secondary materials have difficulty competing with virgin materials. The reasons they note are essentially two fold.First, the salvage industry by its nature has not experienced technical advances to the degree that industry involved in the extraction and processing of virgin materials has. Consequently, as labor costs have risen, recycled materials have been priced out of the market. Secondly, and largely for historical reasons, the costs of virgin materials have in recent years not reflected the true social and economic costs of those materials. In particular, Darnay and Franklin cite the presence of depreciation allowances, environmental externalities, and balance of payments effects as added costs that are unaccounted for. The implication is that if market prices reflected all costs, there would be a greatly increased use of secondary materials. While it is perhaps true that virgin materials are underpriced for all these reasons, we will be concerned only with intervention designed to reflect the social loss from underpriced disposal services. Thus, the resolution of other market imperfections is implicitly left to other government agencies.

VIRGIN MATERIALS TAX

There are two general ways that disposal costs can be brought to bear on relative market prices: the solid waste authority can introduce taxes that will raise the cost of virgin materials or can, through the use of subsidies,reduce the price of secondary materials relative to virgin materials. In either case, the result is an increased demand price for recycled materials. This is then either passed on to waste disposers in the form of high payments for recycled wastes, or is utilized to finance increasingly intensive collection efforts by junk dealers, civic groups, and other elements of the salvage industry. The net result is an increased volume of waste being recycled.

The most significant difference between the two approaches is that intervention through taxation of virgin materials, in addition to increasing the use of recycled materials, raises the cost of production and therefore reduces the output of industries that use the virgin materials as a factor of production. Which type of policy is most appropriate will depend on a comparison of the welfare effects of a virgin materials tax and a corresponding subsidy, a concept that is developed more precisely below.

The effects of a tax are essentially two fold. First, the price of virgin materials is raised and the quantity used decreases; second, the demand curve for recycled materials shifts upwards and increasing quantities are recycled.

Because of the peculiar nature of virgin and recycled markets, the dependence between the two is unidirectional (i.e., changes in equilibrium price or quantity of virgin materials does affect the demand for recycled materials, but not conversely). Mathematically this is represented by writing the supply (or marginal cost) curve and inverse demand curve for virgin materials as functions of V the quantity of virgin materials, while the inverse demand curve for recycled materials is written as a function of both the quantity R of recycled materials and the tax τ_V on virgin materials. The reason for the assumed unidirectional relationship is simply because the quantity of materials being recycled is insignificant compared to the quantity of virgin materials being produced (e.g., one would expect recycled aluminum cans to be insignificant compared to the total aluminum production). Thus, while, say, an increase in the quantity of recycled materials may mean that virgin materials have been replaced by recycled materials in some uses, the virgin materials market will be essentially unchanged (of course significant interaction of the virgin and recycled markets would occur if the recycled market was of significant size relative to the virgin market). Because of this, for all practical purposes, the welfare

gains or losses from each of the two effects may be thought of as being independent (i.e., the net benefits of the two effects together is equal to the sum of the net benefits of each effect separately).

Figure 10 is a graphical representation of the effect of the introduction of a virgin materials tax. As a result of the imposition of the tax τ_V, the supply curve for virgin materials shifts up by the amount of the tax which leads to reduced consumption of virgin materials and increased substitution into recycled materials. This is shown in the figure by the demand curve shifting from $D^{-1}(R;o)$ to $D^{-1}(R;\tau_V)$ where the shift is a constant amount $K(\tau_V)$. Notice though that market conditions would be identical if the shift in the demand curve had been precipitated by the introduction of a subsidy to the use of recycled materials in the amount of $K(\tau_V)$. Thus to any virgin materials tax τ_V we can think of a corresponding subsidy of $K(\tau_V)$ where $K(\tau_V)$ is the amount of vertical shift in the demand for recycled materials as a function of τ_V. But it is now obvious that the welfare gain or loss, resulting from changes in the market for recycled materials, associated with tax τ_V (including not only the welfare effect of the increased recycling, but also the reduced demand for waste disposal services) is the same as the welfare effect of the equivalent subsidy $K(\tau_V)$.

Thus, the argument for using a virgin materials tax in preference to a subsidy must rest with the welfare effect of the tax within the virgin materials market. This welfare effect, of course, includes not only the ultimate loss in consumer utility from reduced consumption, but also the changed (probably reduced) demand for disposal services that follows from the reduced consumption and new techniques of production employed. The welfare effect from such a tax was, however, discussed in Section VI where factor taxation was considered. At that time it was pointed out that the informational requirements of optimal taxation at that level were

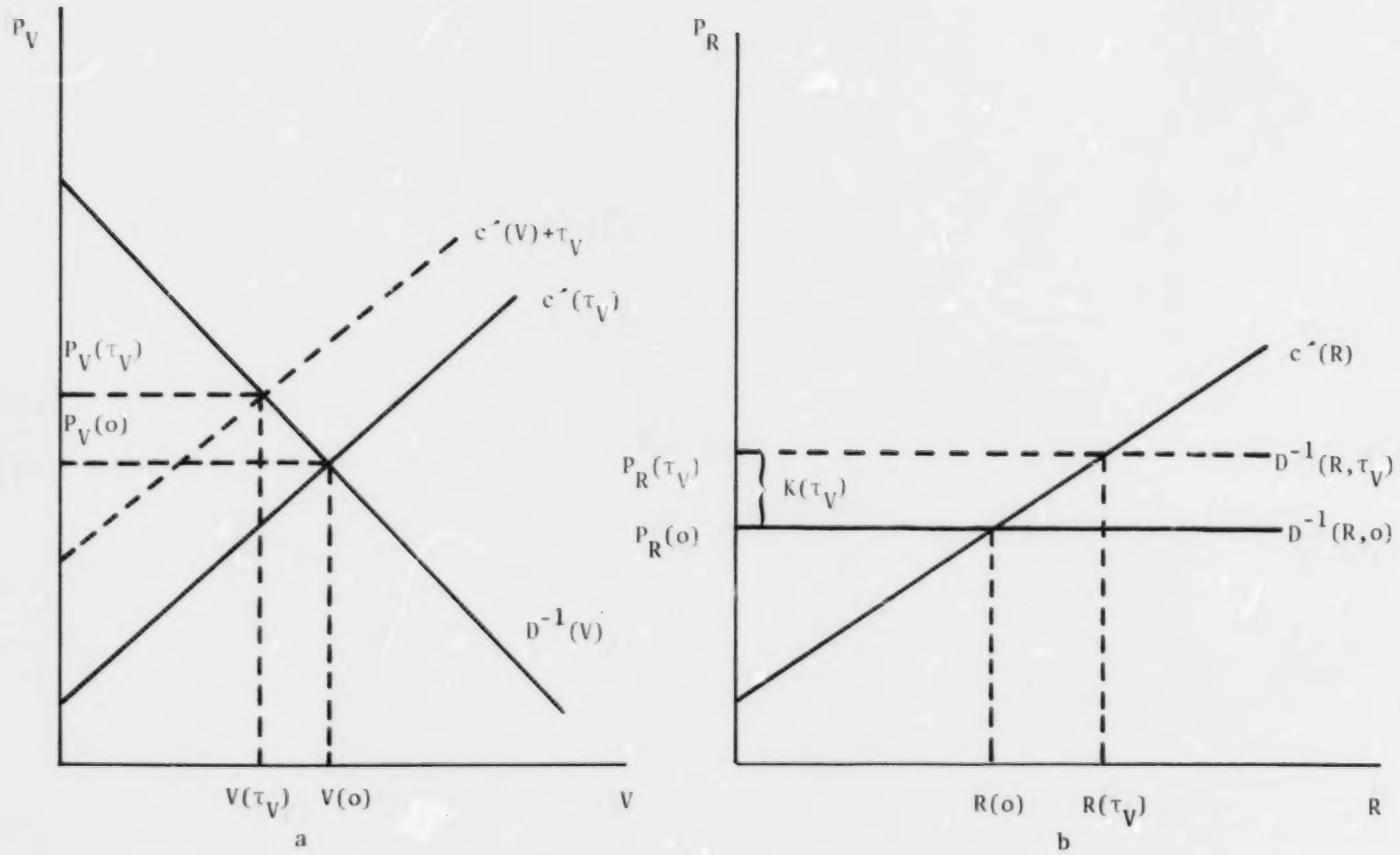

Figure 10. Effect of virgin materials tax on the markets for virgin and recycled materials

excessive and that there was a high probability of undesirable secondary effects. It was finally argued that most probably other approaches (in particular a waste tax) would be preferable. For all these reasons it is almost certain that a virgin materials tax is inferior (as a policy tool) to the combined use of recyling subsidies and other tools (e.g., waste disposal taxes) designed to control the rate of generation of waste.

SUBSIDIES

We now turn to a consideration of optimal subsidies to encourage recycling. Subsidies can, of course, be applied in any of a number of different stages of the recycling process and in general the welfare effects may not be the same. For example, the SWA could subsidize products that use secondary materials, the processing of these materials, or their collection. It appears though that intervention at any point other than the collection stage will be unable to meet the precise needs of each individual community. The reason is that a subsidy at some other level (e.g., processing of wastes for recycling) would shift the demand price for recycled materials up by the same amount (neglecting transportation costs) in all communities that send wastes to that processor. On the other hand, one would expect that the optimal subsidy from the point of view of each community separately would vary with the particular collection and disposal techniques being used there. For example, suppose that to encourage the recycling of paper a subsidy to recycled pulp is instituted at the pulping stage. If in some community wastes are burned to generate power, then such recycling could actually be detrimental on any level. Thus, the optimal subsidy from the point of view of a community using wastes for power generation may be zero or even negative. In general, then, one would expect that the welfare maximizing approach would be for each community to set its own subsidy level. Total welfare would then be at least as great as for a single subsidy level applied to several communities. The point at which to intervene, then, is the level of local collection.

In the analysis that follows, it is assumed that a subsidy is offered to encourage the recycling of a specific waste type i (e.g., old newspapers). Subsidies are paid to authorized scavangers, salvage dealers, and civic organizations on the basis of a fixed price for each unit of the specific waste recycled (i.e., collected and turned over for processing). In actuality little more than notational difficulties are involved in extending the results developed here to subsidies on several waste types simultaneously.

The use of the generalized welfare measure is impractical in the case of a subsidy because of the difficulty in predicting the effect of a subsidy on all markets for consumer goods. Instead, the welfare effects of a subsidy will be measured by the more standard area between the demand and marginal cost curve in the effected markets. In the case of a subsidy the effected markets can be thought of as the market for recycled materials, the market for disposal services, and the markets for all consumer goods. It will be assumed that markets for all consumer goods operate competitively and that there is no change in equilibrium price there. Thus, the effects in these markets may be ignored. This is in fact intuitively plausible since one would expect the effect of a subsidy to be diffuse enough at this point that the welfare effects would be negligible compared to the primary effects in the recycling and disposal markets.

It will be convenient for the analysis that follows to conceptually separate the recycling markets into two parts. The first reflects the quantity of residuals of type i which are generated before the subsidy is imposed and are recycled after it is imposed. In Figure 11 $\bar{R}_i$ represents the total quantity of residuals of type i which were generated before the subsidy; i.e., $\bar{R}_i$ includes residuals that were either disposed of or eventually recycled prior to the subsidy. The quantity of those residuals that will be recycled as a function of the price being paid for those residuals (denoted by P_i) is given by the function $\sigma_i(P_i)$. This is essentially a supply curve for residual i and consequently the inverse supply function,

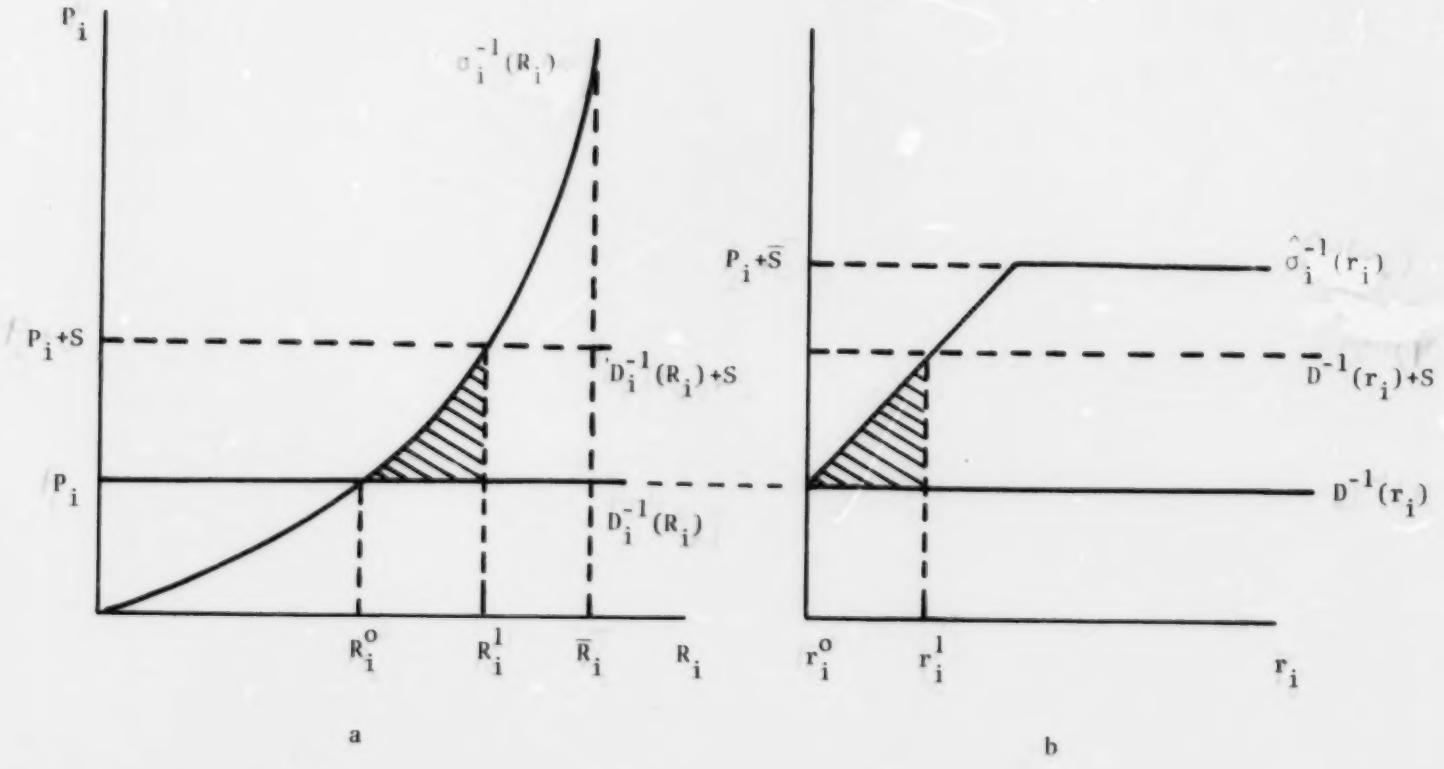

Figure 11. Welfare effect of increased recycling due to a subsidy

$\sigma_i^{-1}(P_i)$, reflects the marginal cost to society in terms of the monetary value of resources expended for recycling. Correspondingly, $D^{-1}(R_i)$ represents the marginal value of the recyled materials to society. Neglecting for the moment the resource saving in a reduced disposal service demand, the welfare cost to society (corresponding to the first component of the recyling market) of a subsidy S is then given by the shaded area in Figure 11a.

The second component as shown in Figure 11b represents the increased quantity of type i residuals generated, denoted r_i, as a function of P_i. This occurs because the effect of a subsidy (to the extent that it is passed on to those who generate residuals as an inducement to turn over recylable wastes) is to reduce the price of goods generating the subsidized residual to those consumers and firms that engage in recycling. The increased quantity of recycling here as a function of $P_i + S$ is represented by $\hat{\sigma}_i(P_i+S)$. Here, $\hat{\sigma}_i^{-1}(r_i)$ represents again the marginal monetary value of resources expended for recyling, but also includes the difference between the cost of the good generating residual i and the value of the use of that good. This last component enters because households and firms will be using goods that have a marginal value in use less than their cost because of the increased monetary value of the residuals in recycling. Thus the shaded area in Figure 11b includes the net welfare loss from the increased use of goods generating residual i induced by the subsidy.

It should be noted that the upward slope of $\sigma_i^{-1}(r_i)$ depends on the assumption that, to some extent, the subsidy is passed on to households and firms generating residual i. If on the other hand the subsidy is completely absorbed in increased costs of collection, then this curve would be vertical and the welfare loss in Figure 11 would vanish. Also note that a critical point is found at $P_i+\bar{S}$. This represents the point where the per unit value of the residual i in

recycling (including the subsidy) equals the cost of producing that residual. Subsidies in excess of the amount $\bar{S}$ will yield an immediate profit to salvage dealers who can purchase a product producing residual i and resell it as a secondary material at a higher price. In general, the problem posed by this phenomena are moot but perhaps should not be totally ignored.

Finally, we turn to the effect on disposal costs of the subsidy. Again the effect can be separated into two components. First, there is the quantity of residual i offered for disposal as a function of S. This is denoted by $W_i(S)$ in Figure 12. Secondly, there is the quantity of all other wastes offered for disposal as a function of S. This is denoted by $W_{i-}(S)$. This will in general not be a constant function because (to the extent that the subsidy is passed on to firms and households) consumption and production decisions and hence wastes generated will be affected by the subsidy. While $W_{i-}(S)$ has been shown as decreasing for values of S in a neighborhood of 0, there is no a priori reason why it would not be an increasing function throughout. Finally, $W_{i-}(S)$ will be increasing for large values of S because of an income effect; as the monetary value of the subsidy becomes large, it will induce increased consumption and increased wastes. This however, neglects the fact that subsidies of this magnitude will probably necessitate increased taxes which would have an opposite income effect.

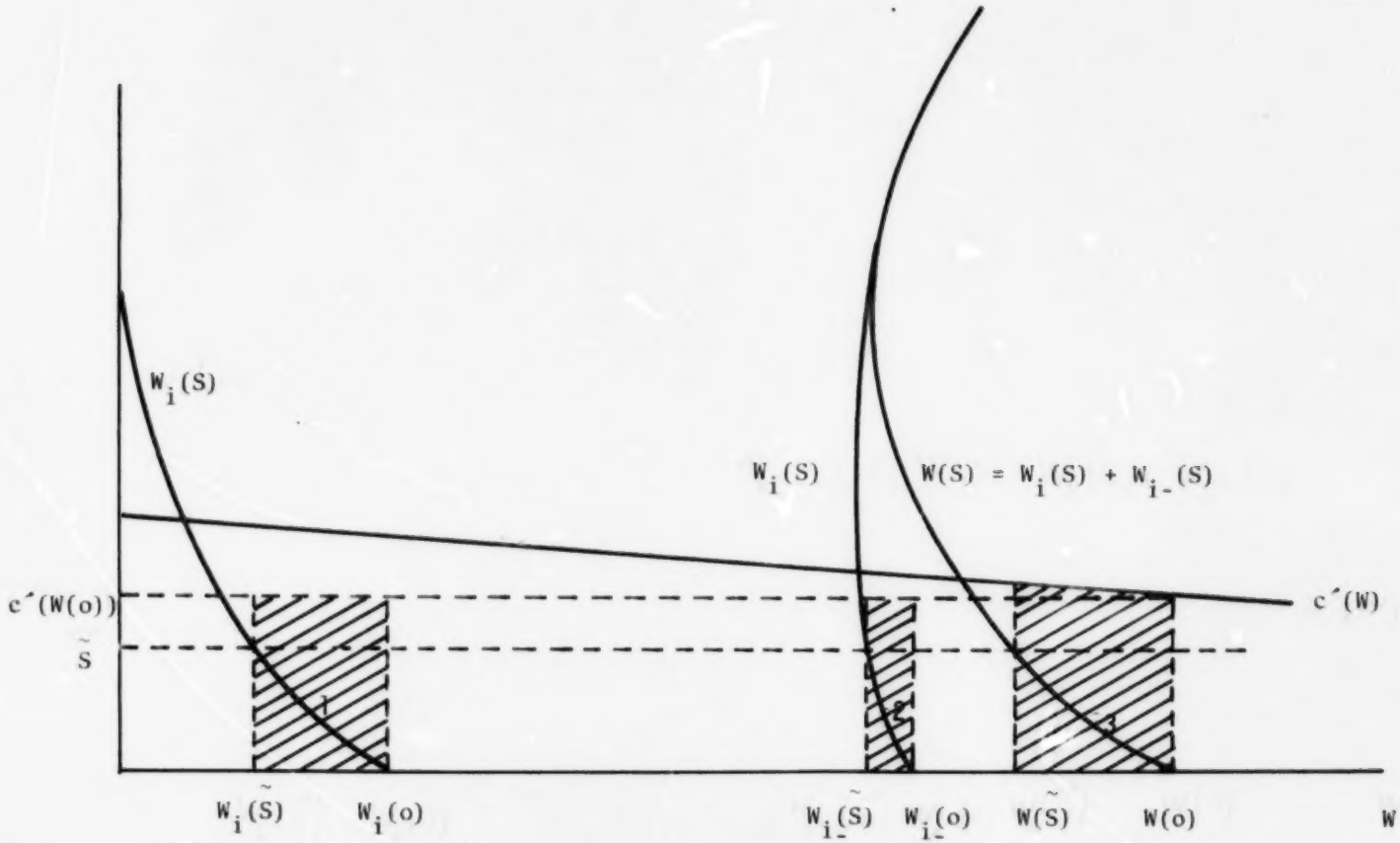

Figure 12. Welfare effect of reduced demand for disposal servies due to recycling subsidy

The aggregate waste function is $W(S) = w_i(S) + W_{i-}(s)$. For any subsidy level, say S, the welfare gain from reduced expenditures on disposal services is given by the area under the marginal disposal cost curve c´ between W(S) and w(o). This is just shaded area 3 in Figure 12. This is, of course, approximately equal to the sum of areas 1 and 2 and is in fact exactly equal if the marginal disposal cost curve c´(W) is constant between W(S) and W(o).

Now putting all components of the welfare effect together, we can mathematicall represent the net benefits to a subsidy of S to the recycling of residual type i as

$$\int_{W(S)}^{W(o)} c'(z)dz - \int_{P_i}^{P_i+S} [\sigma_i(P_i+S) - \sigma_i(z)]dz$$

$$- \int_{P_i}^{P_i+S} [\hat{\sigma}_i(P_i+S) - \hat{\sigma}_i(z[)dz \qquad (111)$$

If in fact the subsidy is not passed on to consumers and firms, or if we are willing to assume that the effect on consumption and production decisions is negligble if passed on, this simplifies to

$$\int_{\bar{W}_{i-}+W_i(S)}^{\bar{W}_{i-}+W_i(o)} c'(z)dz - \int_{P_i}^{P_i+S} [\sigma_i(P_i+S) - \sigma_i(z)]dz \qquad (112)$$

where $\overline{W}_{i-}$ is the now constant amount of other types of wastes generated and the last term of expression (111) has now vanished. Notice though that by integrating the second term along the R_i axis instead of the P_i axis this becomes

$$\int_{\overline{W}_{i-}+W_i(S)}^{\overline{W}_i+W_i(o)} c'(z)dz - \int_{\sigma_i(P_i)}^{\sigma_i(P_i+S)} [\hat{\sigma}_i^{-1}(z)-P_i]dz \quad . \qquad (113)$$

But by the simplifying assumptions that have been made each additional unit recycled represents exactly one unit less of wastes offered for disposal. Thus in fact

$$W_i(S) = \overline{R}_{i-} - \sigma_i(P_i+S) \quad ; \qquad (114)$$

thus we can write

$$\int_{\overline{W}_{i-}+\overline{R}_i-\sigma_i(P_i+S)}^{\overline{W}_{i-}+\overline{R}_i-\sigma_i(P_i)} c'(z)dz + \int_{\sigma_i(P_i+S)}^{\sigma_i(P_i)} [\sigma_i^{-1}(z)-P_i]dz \qquad (115)$$

Finally, through a change of variable we see this is equal to

$$\int_{\sigma_i(P_i+S)}^{\sigma_i(P_i)} [c'(\overline{W}_{i-}+\overline{R}_i-z) + \sigma_i^{-1}(z) - P_i]dz \qquad (116)$$

Differenteation yields the first order condition for a maximum:

$$c'(\overline{W}_{i-} + \overline{R}_i - \sigma_i(P_i + S)) = S \qquad (117)$$

or

$$c'(W(S)) = S \quad . \qquad (118)$$

This gives the familiar condition that the subsidy should be set equal to the marginal cost of disposal that results from the subsidy.

It will be instructive to consider graphically the derivation of this fact. In Figure 13 $\bar{R}_i$ again denotes the now fixed quantity of residual i available for disposal or recycling. The inverse supply curve for residual i (actually it now represents a marginal cost to collection for recycling since there are no payments to firms or individuals generating residual i), $\sigma_i^{-1}(R_i)$, is the same in Figure 11. The total wastes being disposed of for any given level of recycling R_i is then given by the sum of the constant amount of other wastes for disposal $\bar{W}_{i-}$ plus the quantity of residual i that is not being recycled $\bar{R}_i - R_i$. Thus the marginal cost of disposal of one unit of residual i as a function of R_i is given by $c'(\bar{W}_{i-} + \bar{R}_i - R_i)$. The total marginal benefits of recycling are then given by the sum of the marginal value in recycling plus the marginal value in reduced demand for disposal services. This is given by $D^{-1}(R_i) + c'(\bar{W}_{i-} + \bar{R}_i - R_i)$. As discussed earlier, $\sigma_i^{-1}(R_i)$ represents the marginal social costs of recycling. The optimum is then defined by the equation

$$\sigma_i^{-1}(R_i) = P_i + c'(\bar{W}_{i-} + \bar{R}_i - R_i) \quad . \tag{119}$$

Writing R_i as a function of P_i+S and noting that it is just the function σ_i, this becomes equation (117). This defines the optimal subsidy as S^* and the corresponding optimal level of recycling as R_i^*. The increment to benefits is given by the shaded area.

From a practical point of view, it is important to consider the financial impact of such a subsidy on the SWA. Figure 14 is essentially a duplicate of Figure 13 except that the shaded areas now represent the actual monetary costs and savings of the program to the SWA. The area A_1 represents subsidy payments by the SWA. The area A_2 represents the monetary savings from reduced demand for services. It is highly probable that the net result given by A_2-A_1 is a significant cash outflow for the SWA. It should be emphasized that this in itself is not a social welfare loss by our measure since it merely represents a

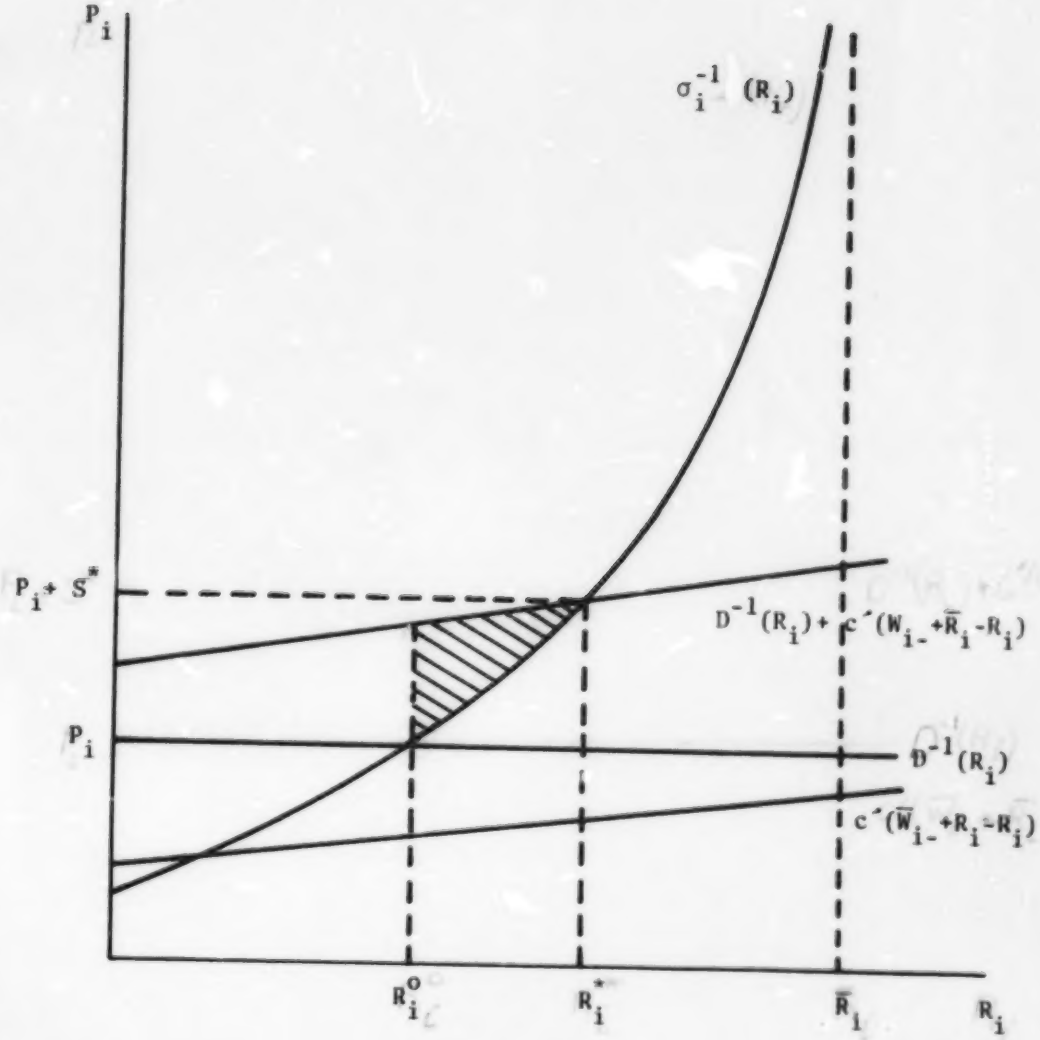

Figure 13. Optimal subsidy and corresponding welfare effect

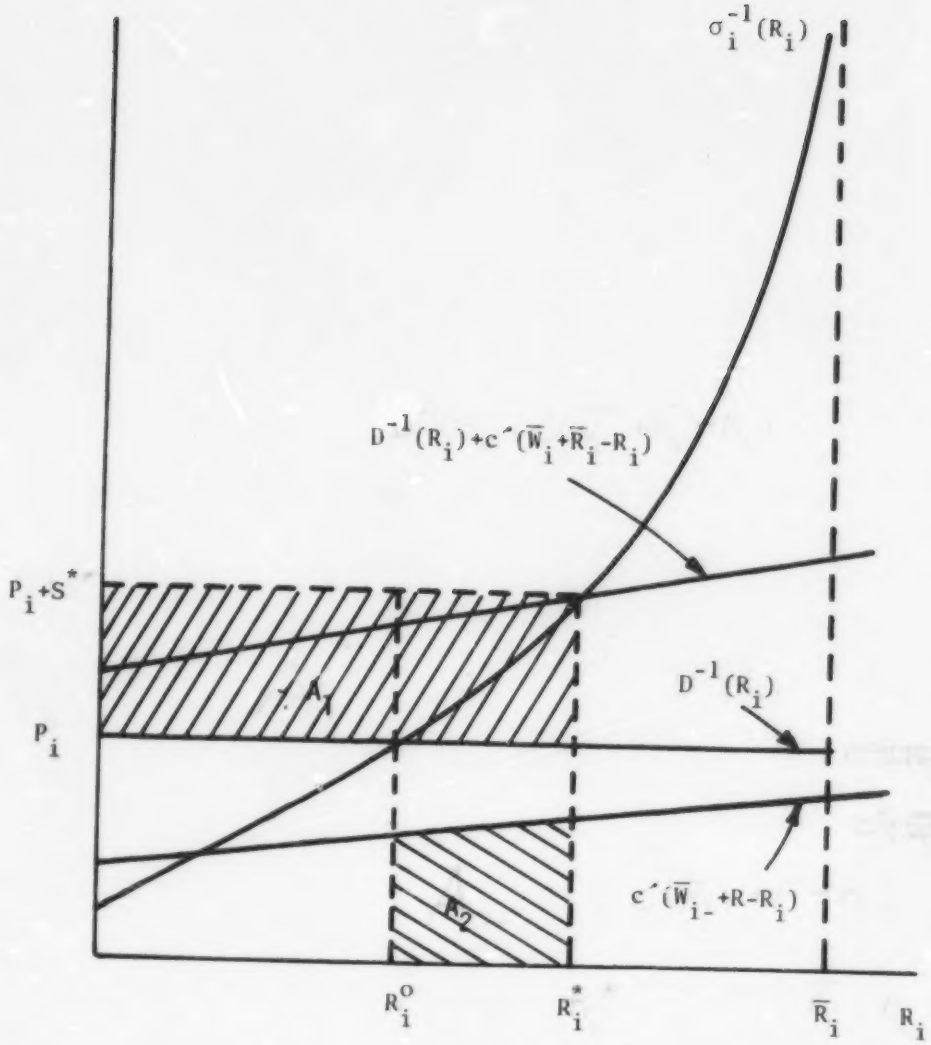

Figure 14. Monetary cost to SWA of an optimal subsidy

redistribution of income. Nevertheless, this amount may be significant in light of the financial constraints that usually beset municipal disposal services.

In essence the optimal subsidy under the simplifying assumption imposed is equal to the marginal cost of disposal services. The situation is very similar to the marginal cost taxing model of the previous section. Just as was the case there, the determination of optimal subsidies in practice will involve an iterative approach. The various potential problems and practical methods of dealing with them are essentially the same as discussed in the taxing section and so will not be repeated here.

As was discussed above, in order to maximize benefits from a subsidy scheme, the subsidy must be applied on the local level to the firms, individuals, and organizations involved in the collection of wastes. On a practical level this has problems too. As was noted earlier, there is the possibility of an arbitrage scheme whereby there is a profit to be made in the creation of wastes and their recycling. More difficult is the problem of monitoring the quantities recycled. Presumably payments could be made on the basis of signed receipts from processors, specifying the amounts recycled by a particular salvage agent. Even this would not preclude fraud. Finally, the local SWA using subsidies may not be able to effectively distinguish between wastes being collected for recycling from its own community and from other areas. Thus there is the danger that one community will find itself subsidizing the recycling of wastes from other communities. It appears that unless it is possible to overcome the financial constraints and to devise effective techniques of monitoring the system, another approach must be sought.

SALVAGE ACTIVITY BY THE SWA

In order to avoid these drawbacks it may be desirable for the solid waste authority to enter the salvage industry itself and provide collection and possibly processing services for recyclable items in addition to its traditional disposal duties. If the industry is

characterized by economies-of-scale, as seems probable, by its size alone the SWA would have an advantage. If it is possible to combine collection of recyclable items with collection of wastes for disposal, the SWA would have an additional comparative advantage. The City of Madison has in fact done just this for recycling newsprint. By adding baskets on the sides of the collection trucks, it has been possible to collect bundled newspapers at the time of the regular collection.

The welfare analysis that follows continues with the assumption that there is no effect on household consumption decisions or firm production decisions within the municipality adopting the program. Thus the welfare effects can be graphically represented in a fashion analogous to Figure 13 . In that case though the supply curve represented the marginal costs to collection and delivery of recyclable materials. In Figure 15 this curve is divided into two components. First there is the marginal costs to the SWA of collection, delivery, and processing, if any, as given by $\hat{c}'(R_i)$. Since there is presumably some fixed costs in such a venture (e.g., capital equipment purchases and initial set up costs), the marginal cost curve is falling for a range about the origin. Second, there is the marginal cost, $\tilde{c}'(R_i)$ to the SWA to induce firms and households to separate and set out for collection an additional unit of residual i. One can think of this as the price that must be paid per unit to households and firms. In many cases, though, it may be impractical to actually pay for wastes sorted and set aside for recycling by the SWA. In such cases people could be encouraged to cooperate through an advertising campaign. Then $\tilde{c}'(R_i)$ should be thought of as representing the marginal advertising expenditure and would be denoted $a(R_i)$.

In the analysis that follows it is assumed that there are no direct payments made to firms or households providing recyclable wastes, but that cooperation is achieved through advertising.

The total marginal costs to the SWA of recycling, including collection costs and payments or advertising expenditures, is given by

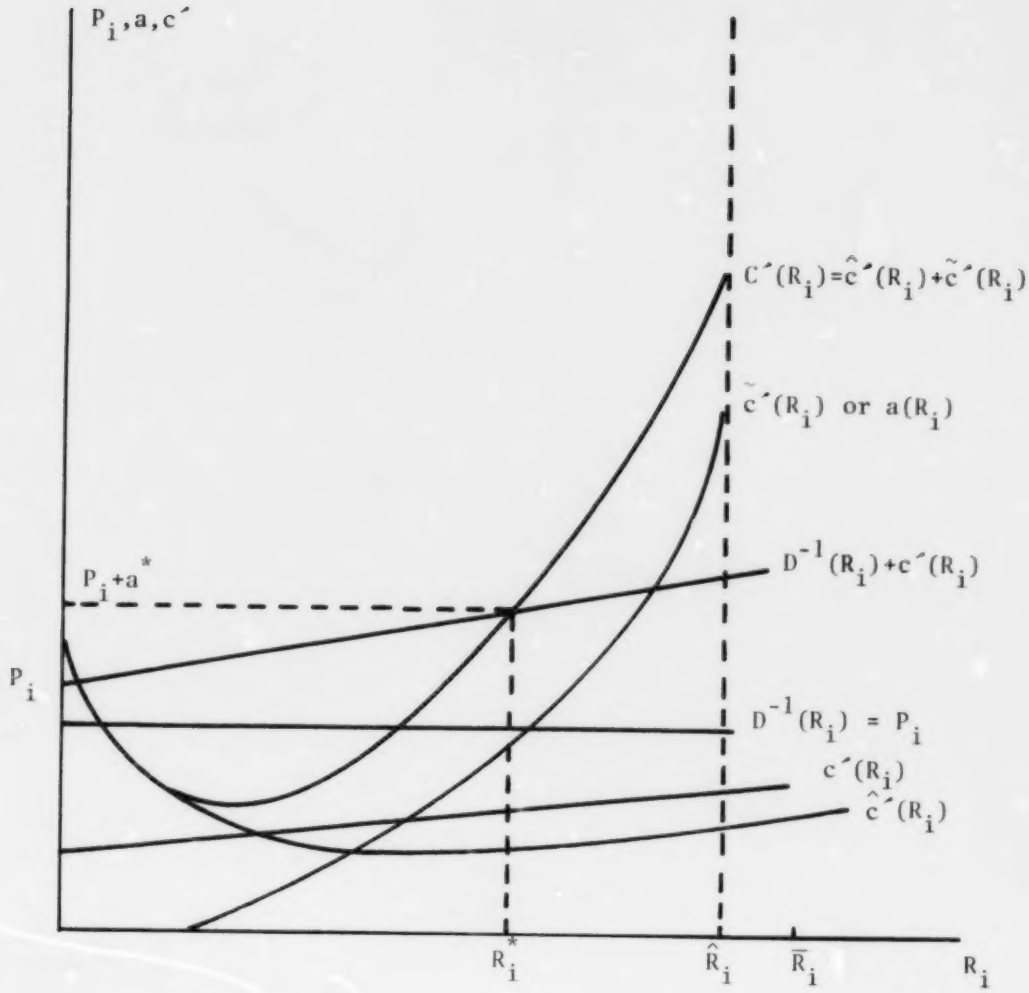

Figure 15. Optimal advertising by SWA in Support of its own salvage program

$C'(R_i) = a(R_i) + \hat{c}'(R_i)$. As before, the monetary measure of the benefits to society of recycling is given by $D^{-1}(R_i) + c'(\bar{W}_{i-} + \hat{R}_i - R_i)$ where $\hat{R}_i$ represents the total quantity of residuals of type i available for recycling by the SWA. It differs from $\bar{R}_i$, the total residuals of type i generated, by the amount of residuals recycled privately. Private recycling is assumed to be a constant with respect to the advertising expenditures by the SWA. This is somewhat plausable since private recycling is for the most part done by firms because of a profit motive. Since the SWA will not be making payments, the same profit situation will prevail independently of the advertising and hence the private recycling decision should remain essentially unchanged.

The objective of the SWA should therefore be

$$\max_{a} \int_{0}^{C'^{-1}(P_i+a)} [P_i + c'(z) - C'(z)]dz \quad . \tag{120}$$

Such a maximum is found in the figure at the point R_i^* where

$$P + c'(R_i^*) - C'(R_i^*) = 0 \quad . \tag{121}$$

Of course, even if the first order condition is satisfied, the decision of whether such a program should be undertaken must be based on whether or not total costs are above total revenue to the SWA. This is of course essentially what the optimization problem above says; if

$$\int_{0}^{R_i^*} [P_i + c'(z) - C'(z)]dz < 0 \quad , \tag{122}$$

then the optimum value of a is zero (i.e., the program should not be instituted). In practice it will be very difficult to estimate the

curve $\tilde{c}'(R_i)$ and hence there is little indication whether there is any value in the SWA entering the salvage industry, let alone how to do so optimally.

The only practical approach may be to try such a program in a representative neighborhood of the city to gain an indication of the response of waste generating units. The practicality of this type of a program will probably vary significantly from city to city (and perhaps within a given city), depending to a large extent on the social and environmental awareness of the population.

There is one final point worth noting and that is if a waste disposal tax $\bar{\tau}$ is already in effect, the optimization problem (120) will set the marginal advertising expenditures at a level in excess of the optimal. The reason is that taking the tax as given, the real value of resources expended in recycling the last unit of residual i now includes not only the marginal advertising expenditure $\tilde{c}'(R_i)$ plus the marginal collection and treatment costs for recycling $\hat{c}'(R_i)$, but also the marginal cost to firms and households of preparing residual i for collection. The final cost by the theory of microeconomic optimization will at the margin just be equal to the tax $\bar{\tau}$. The new situation is depicted in Figure 16. The only change over the previous graph is that the tax $\bar{\tau}$ has been subtracted from the marginal benefits to recycling as represented by $D^{-1}(R_i) + c'(R_i)$. It can be seen that the optimal level of recycling and the optimal advertising expenditure are decreasing functions of τ.

In areas that are relatively unresponsive to advertised appeals for cooperation with the solid waste authority's salvage program, the additional use of a waste disposal charge may be effective. By charging for disposal services, but collecting items for recycling at a reduced, zero, or even negative charge, there will be the added monetary incentive to sort out and set aside recyclable items. By providing this recycling alternative to disposal, the demand function for disposal services should shift in such a way as to be more

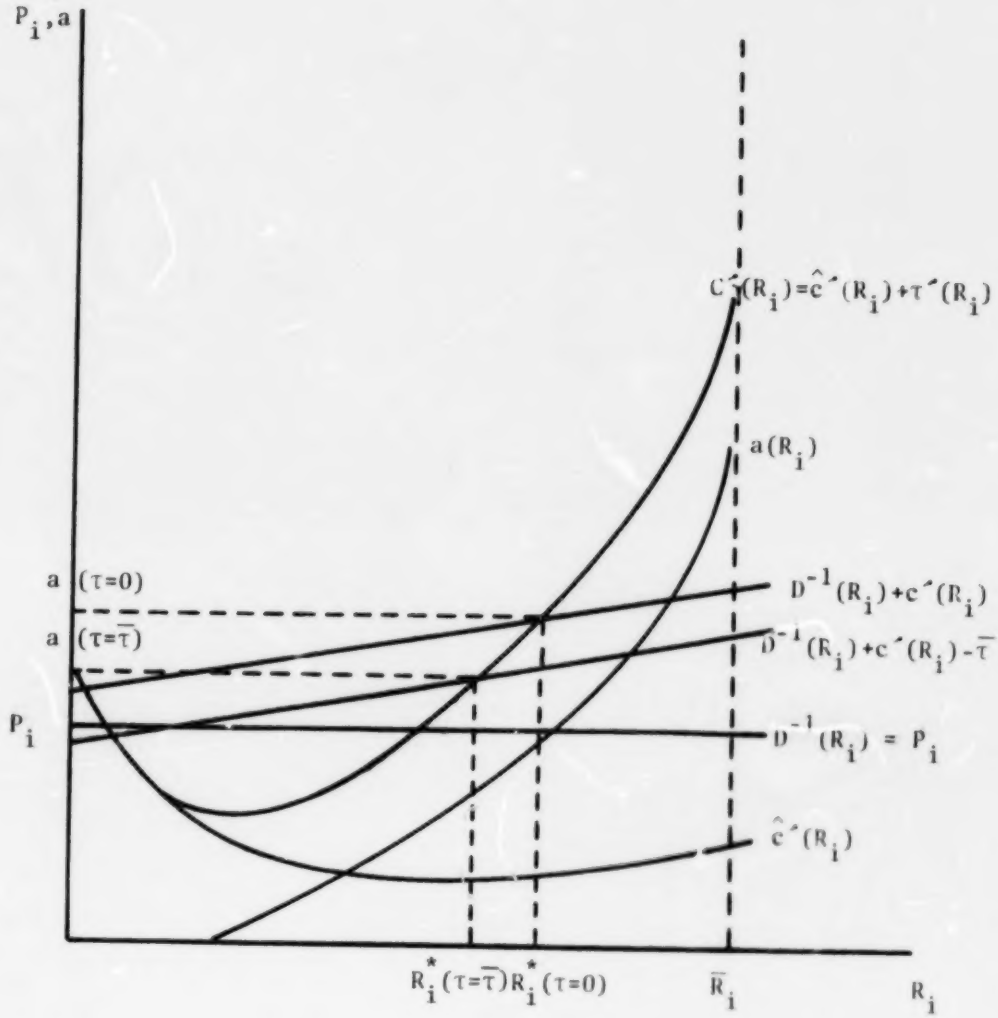

Figure 16. Optimal advertising by SWA in the presence of a solid waste disposal tax

elastic at the lower values of τ, the disposal service tax. Thus while marginal cost taxes and entry into the salvage industry, combined possibly with subsidies, may as isolated policies be ineffective for the solid waste authority, they may be complementary in that when combined the result is a significant addition to social welfare.

However, the optimization over both τ and a simultaneously is not a straight forward problem. A solution will require first the derivation of the optimal advertising expenditures as a function of the tax. This function will be denoted by $A^*(\tau)$. Secondly, it will be necessary to define the optimal tax as a function of the advertising expenditure. This function will be denoted by $\tau^*(A)$. An optimal solution will then be the pair A^*,τ^* where

$$A^*(\tau^*) = A^* \tag{123}$$

and

$$\tau^*(A^*) = \tau^* \tag{124}$$

The derivation of the optimal marginal advertising expenditure on page 116 can be used to define the optimal total advertising expenditure through the integral

$$A^*(\bar{\tau}^*) = \int_0^{R_1^*(\tau^*)} a(z)dz \quad . \tag{125}$$

The derivation of the optimal tax taking A as given at $\bar{A}$ is a bit more complicated. The effect of a tax can be conceptually compartmentalized into two components: First, the effect on the demand for services for non recyclable itmes, and, second, the effect on the recycling market. Figure 17 illustrates these two effects. In Figure 17a the disposal demand curve for non recyclable items is shown. This curve is of course independent of a. In Figure 17b the marginal costs and benefits of recycling are shown for A fixed at $\bar{A}$. In both

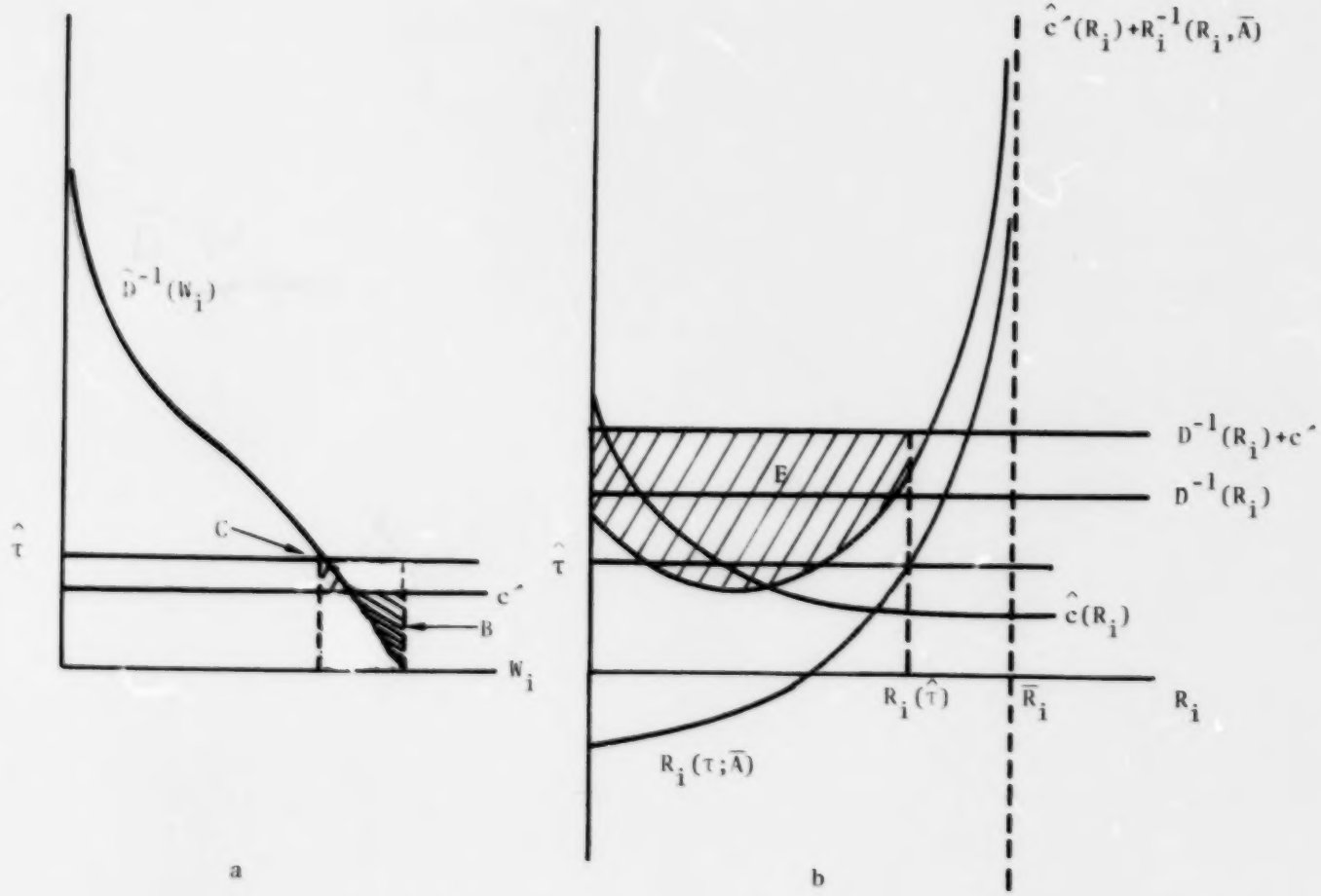

Figure 17. Optimal solid waste disposal tax given advertising expenditures

figures the marginal disposal cost $c'(R_i)$ has been taken as constant to simplify the analysis. In Figure 17 $R_i(\tau;\bar{A})$ is the supply curve for recycled residuals as a function of the disposal tax τ and is parameterized on the level of advertising expenditure $\bar{A}$. It is shown dipping below the origin to denote that to a certain extent firms and households may get a positive value from engaging in recycling activities. The net marginal social benefit from recycling is given by

$$D^{-1}(R_i) + c' - \hat{c}'(R_i) - R_i^{-1}(R_i;\bar{A}) \tag{126}$$

The net marginal social benefit from reduced demand for disposal of other wastes is given by

$$c' - \tilde{D}^{-1}(W_i) \tag{127}$$

where $\tilde{D}^{-1}(W_i)$ is just the inverse demand for W_i . Noting that R_i is a function of τ and $\bar{A}$ the first order condition for a maximum is given by

$$[D^{-1}(R_i) + c' - \hat{c}'(R_i) - R_i^{-1}(R_i;A)]\frac{dR_i}{d\tau} + [c' - \tilde{D}^{-1}(W_i)]\frac{dW_i}{d\tau} = 0. \tag{128}$$

Solving this then defines the optimal τ as a function of A, $\tau^*(A)$. Working with the optimal tax parameterized on A and the optimal advertizing expenditure parameterized on τ, the system can be solved for the fixed point.

While the approach here has been graphed in order to make the situation and its solution more intuitive, it should be noted that the total change in benefits to society from the joint imposition of a tax τ and advertising expenditure A can be represented by

$$\int_{\tilde{D}(\tau)}^{\tilde{D}(o)} [c' - W_i^{-1}(z)]dz + \int_{o}^{R_i(\tau;A)} [P_i + c' - \hat{c}'(z) + R_i^{-1}(z;\bar{A})]dz - A . \tag{129}$$

In the figure the first integral equals area B minus area C, while the second integral is just equal to area E.

The optimization problem discussed here is, of course, quite informationally intensive, and probably highly costly to solve explicitly. A much more practical approach, which neglects the information costs, is to use marginal cost taxing and then choose the optimal level of advertising expenditure taking the tax as fixed. In practice there are difficulties (though not insurmountable) with this approach since the marginal disposal costs will in general not be a constant, but will vary with the quantities handled and hence with the level of advertising and the tax. Note though that if the marginal disposal cost curve c' is comparatively flat, a reasonable procedure may be to simply set the tax initially at $c'(W^o)$ where W^o is the initial demand for disposal services. With the tax fixed, the optimal marginal advertising expenditure is defined. This, however, must be translated into an optimal value for A, the total advertising budget since it is in fact the decision variable. To compute this directly though would require knowledge of the $a(R_i)$ function. In practice this informational requirement may not be a significant obstacle since the decision variable A actually represents the steady state quantity of advertising. When the program is initiated, it will be necessary to engage in a large scale once-and-for-all advertising campaign to make people aware of the program. A reasonable approach to the problem then is to gradually reduce the amount of advertising expenditures after the initial outlay and thus empirically estimate the curve. The SWA can then hold advertising expenditures constant when it observes the marginal condition to be satisfied.

Once this steady state optimal advertising budget is found, a decision to readjust the tax rate can be made. The important point to note is that while for taxes to be effective they must be subject to as little variation as practical, there are no adverse effects from fluctuations in the advertising budget. The extensive experimentation to define the optimal level of advertising expenditures is

feasible and perhaps desirable.

On a practical level, the waste type that would most readily lend itself to this type of approach to recycling is newspapers. One would expect a relatively elastic supply curve since the disutility associated with handling them separately would probably be less than for virtually any other item. Furthermore, because of their bulk, households would probably view the disposal charge on newspapers (if they were not sorted) as significant. Also, newspapers constitute a significant enough portion of municipal waste so that the recycling of even 25 or 30 percent of newspaper waste would result in a significant reduction in waste volume. Finally, the current situation in the paper market has seen a sharp rise in the demand price for recycled newsprint over the last year.

The same approach could be utilized for the recycling of a number of different waste types including metals, glass, and waste paper. The practicality of this approach would have to be gaged separately for each item. In some cases the demand price for the recycled material may be insufficient to justify the effort; in others it may be too costly to get an adequate level of cooperation. These issues would have to be decided case by case. At the least, the combination of a solid waste disposal tax with the intervention of the SWA into the salvage market appears to be a potentially useful tool, the merits of which must be judged by each municipality separately.

The results presented here represent the situation facing a muncicipality acting alone. Darnay and Franklin claim that the demand for recycled materials is in fact fixed (presumably because of a capacity constraint at the processing stage). Hence, the effect of increased recycling in one community is merely to reduce the level of recycling in other communities. In particular, they point out that Madison was only able to sell the paper collected by the disposal authority by establishing a long term contract with a deinking plant outside of

Chicago. The net result of the contract was that papers that would have been accepted from private dealers in Milwaukee, Madison, Chicago, Gary, and other surrounding cities,are now only accepted to the extent that the supply from the Madison disposal authority falls short of the plant capacity. To the extent that this is a general phenomena, actions that will benefit an individual municipality will actually be counter productive from a larger regional approach.

It would seem most likely that the persistant existence of an excess supply of recycled materials follows from the necessity processors face to ensure the full utilization of capacity in the face of a supply that fluctuates widely and rapidly. The information costs necessary to constantly clear the market are probably excessive compared to the value obtained. Thus to avoid large inventory costs, price is set to guarantee that supply is rarely difficient. If processors could be assured of a constant supply of materials, then the incentive might exist to invest in capital expansion. Such an assurance, however, would in most cases have to be forthcoming from a number of cities in a region in order for there to be sufficient volume to induce capital expansion. It would then appear desirable to coordinate action over several waste regions, even out stochastic supplies, and perhaps, if necessary, engage in the necessary capacity expansion to utilize the supplies available.

SECTION IX

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